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EVALUATION OF RUBBER MODIFIED ASPHALT DEMONSTRATION PROJECTS

FEBRUARY 1994

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Ministry of
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and Energy

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EVALUATION OF RUBBER MODIFIED ASPHALT DEMONSTRATION PROJECTS

Report prepared by:

John Emery Geotechnical Engineering Limited
(JEGEL-ORTECH)

ACKNOWLEDGEMENT AND DISCLAIMER

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Ontario

Ministry of
Environment
and Energy

Ministère de
l'Environnement
et de l'Énergie

135 St. Clair Avenue West
Suite 100
Toronto ON M4V 1P5

135, avenue St. Clair ouest
Bureau 100
Toronto ON M4V 1P5

Dear Sir/Madam:

Ontario is diverting 40 per cent of its scrap tires from disposal through resale, retreading and value-added products using crumb rubber. Our goal is to increase diversion to at least 60 per cent of the tires scrapped annually in Ontario. One of the ways of achieving this goal is by encouraging the development of Rubber Modified Asphalt (RMA) as a value-added product.

There have been 22 RMA demonstration projects across the province. These projects have helped municipalities clean up half a million scrap tires, pave 125 kilometres of two-lane road and install 3 composting/recycling asphalt pads. The results of the first eleven of these projects are discussed in the attached report that was commissioned by the Ministry of Environment and Energy.

The ministry intends to assess the recommendations in the report over the coming weeks, and to use the results for planning the future direction of the province's RMA program and its scrap tire management strategy. Ontario's Scrap tire management strategy is based on the 3Rs principles of waste management, with an emphasis on the development of markets for value-added products.

If you have any comments on this report, we would be pleased to hear from you. You can send your comments to Ms. Eileen Smith, Waste Reduction Office, at the address indicated above.

Sincerely yours,

Marylee O'Neill
Director, Waste Reduction Office

February 1994

EVALUATION OF RUBBER MODIFIED ASPHALT DEMONSTRATION PROJECTS

EXECUTIVE SUMMARY

The eleven Ontario rubber modified asphalt demonstration projects have been evaluated in terms of pavement performance and environmental impacts, including recyclability, with comparison to the findings of other jurisdictions such as the United States Federal Highway Administration and Environmental Protection Agency. The demonstration projects included: eight rubber modified asphalt concrete (RUMAC) projects in which the recycled rubber from scrap tires (termed crumb rubber modifier, CRM) behaves essentially as rubber aggregate (termed dry process), including one project with recycled rubber modified asphalt concrete (RRUMAC); two rubber modified cold in-place recycling projects (RUMCIP); and one rubber modified asphalt cement (AR) project (termed wet process).

The Ontario generic dry process rubber modified asphalt concrete (RUMAC) and wet process continuous blending asphalt rubber (AR) pavement performance and environmental impacts, including recyclability, findings are very similar to those of the Federal Highway Administration/Environmental Protection Agency (FHWA/EPA) who also considered two of the Ontario rubber modified asphalt demonstration projects (Thamesville Phase I and Haldimand-Norfolk Trial 1). On the basis of short-term performance monitoring experience for eight projects, there is no reason why the quality and performance of properly designed and placed generic dry process RUMAC cannot be equivalent to conventional hot-mix asphalt (HMA). This will require care in: the selection of CRM type, compatibility, grading, composition and content; the modified Marshall method of RUMAC mix design; and the production, placement and compaction of the RUMAC during favourable paving conditions. It should be noted that the comparative pavement performance of RUMAC surface course mixes with relatively high and coarse CRM content has been very poor to poor. For this reason, finer CRM (No. 10 mesh, or finer) has been used at the 1.0 to 1.5 percent addition level in many of the more recent generic dry process RUMAC demonstration projects.

The wet process continuous blending of AR shows considerable promise, based on early (1977 to 1980) and current (Highway 400 test section) Ontario and State (Florida, for instance) experience, and should certainly be pursued. It appears that AR can enhance the durability of dense- and open-graded hot-mix asphalt. One

State (California) has developed an asphalt rubber hot mix gap-graded (ARHM-GG) interim guide which included thinner structural design equivalents. The use of AR in open- and dense-graded friction course, SAM and SAMI applications should also be considered. The wet process continuous blending of AR in Ontario might be best established through technology transfer from the Florida Department of Transportation.

The use of CRM in cold in-place recycling (RUMCIP) cannot currently be considered a technical success as extensive rutting and ravelling were experienced for the two demonstration projects before the placement of the conventional HMA wearing surface. This technology should be checked through a core evaluation program. Economic analyses were not completed on RUMCIP.

The one project (Thamesville Phase II) with the recycling of generic dry process RUMAC (RRUMAC), and the FHWA/EPA findings, indicate no technical problems with the recyclability of RUMAC. It also appears, from the FHWA/EPA study, that there should be no technical problems with the recyclability of AR. However, there is some question concerning the accumulative influence of repeated recycling of RUMAC and AR on mix quality that should be addressed through laboratory and plant testing. While considered unlikely, if any rubber modified asphalt is eventually unsuitable for recycling due to technical or supply factors, there could be significant disposal costs involved.

The economics (life cycle cost) of generic dry process RUMAC binder and surface course pavement use, compared to conventional HMA pavements, does not appear to be favourable, even with waste management incentives, based on Ontario experience and costing. Given the paucity of long-term performance data, the life cycle cost analyses for generic dry process RUMAC must be considered to be preliminary at this time.

The economics (life cycle cost) of wet process continuous blending AR was considered by extending US experience and costing to Ontario for typical surface course pavement. If the incorporation of AR does decrease maintenance cost and/or extend the service life, as anticipated, then there is certainly a potential for considerable savings through this CRM use. This is the position that has been taken by US supplier proponents and several States (Arizona, Florida and California, for instance).

The air emission test results of the conventional HMA and RUMAC processes overlapped and exhibited a wide variability indicating that, except for the compound 4-methyl-2-pentanone (otherwise known as methyl isobutyl ketone or MIBK), there was no discernable difference between the emissions of the two processes. The wide variability is believed to be influenced by plant operation and maintenance practices and not because of differences due to the use of rubber modified asphalt. However, in five of the six demonstration projects where emission testing was conducted, MIBK was emitted during RUMAC production and either not detected or orders of magnitude lower during conventional HMA production. In sufficient quantities, MIBK is a skin and mucous irritant and moderately toxic by inhalation but is not considered a carcinogen.

Occupational health exposures monitored for the two processes also measured overlapping levels that, in most instances, were at or below the detection limits for the compounds of interest. Worker exposures for the two processes of conventional HMA and RUMAC were similar.

The two issues of solid waste leachate and liquid effluent quality have not been characterized for rubber modified asphalt. Although it is believed that these wastes are similar to conventional HMA, until this characterization is undertaken for rubber modified asphalt processes these issues will continue to be raised.

Available asphalt technology whether conventional HMA, RUMAC or AR, is capable of meeting environmental regulatory criteria provided it is designed, managed and operated properly. This applies to air emissions, solid waste, liquid effluents and occupational health.

The Certificates of Approval - Air issued by the Ontario Ministry of Environment and Energy for asphalt plants are used as a mechanism to regulate the environmental performance of the industry. Presently, the asphalt industry considers this permitting process to be restrictive and would consider further permitting for RUMAC or AR to be a deterrent to its application. Joint industry/government discussions on rubber modified asphalt technology and its application in Ontario should be undertaken to resolve these permitting issues.

It is recognized that technical issues still require resolution to optimize the application of rubber modified asphalt technology and that further development will be undertaken in areas such as long-term performance. During this research, the environmental component should not be overlooked when appropriate.

Several asphalt technology and environmental recommendations are given in the areas of: CRM selection; generic dry process RUMAC placement; RUMAC long-term performance; life cycle cost comparisons; wet process continuous blending of AR; test procedures for AR and RUMAC; influence of repeated RUMAC recycling; multiple stack emission tests; potential odour problems; and pavement and recycled RUMAC leachability. The centre of excellence concept, and close interaction with the FHWA, are suggested for dealing with the asphalt technology recommendations. It is important that user agencies, the Ontario Road Builders Association, the Ontario Hot Mix Producers Association and pavement consultants be kept informed, and involved, in the development of CRM use in asphalt paving in Ontario.

PROJECTS DE DÉMONSTRATION
ÉVALUATION DE L'ASPHALTE CAOUTCHOUTÉ

SOMMAIRE EXÉCUTIF

Les onze projets ontariens de démonstration de l'utilisation d'asphalte caoutchouté ont fait l'objet d'une évaluation en termes de la performance des revêtements de chaussée et des effets sur l'environnement, ceci incluant les possibilités de recyclage; cette évaluation incluait la comparaison des résultats avec ceux obtenus par d'autres juridictions, comme aux États-Unis l'Administration fédérale des autoroutes (FHWA) et l'Agence de protection de l'environnement (EPA). La liste des projets de démonstration incluait: huit projets impliquant l'asphalte caoutchouté-béton (RUMAC) dans lesquels le caoutchouc recyclé à partir de vieux pneus (matériau sous forme de petits morceaux, appelé CRM) se comporte essentiellement comme des agrégats de caoutchouc (appelé processus à sec), dont un projet de recyclage d'asphalte caoutchouté-béton (RRUMAC); deux projets de recyclage sur place à froid avec addition de caoutchouc (RUMCIP); et un projet impliquant l'asphalte caoutchouté-ciment (AR) (appelé processus humide).

Les effets sur l'environnement et la performance du revêtement de chaussée générique ontarien réalisé à base d'asphalte caoutchouté-béton (procédé à sec) et de l'asphalte caoutchouté produit en continu par le procédé humide (AR), ceci incluant les caractéristiques de recyclage, sont très similaires aux résultats obtenus aux États-Unis par l'Administration fédérale des autoroutes et l'Agence de protection de l'environnement (FHWA/EPA), qui ont également étudié deux des projets ontariens de démonstration de l'utilisation d'asphalte caoutchouté (Thamesville/Phase I, et Haldimand-Norfolk/Test 1). À partir des résultats de l'observation de la performance à court terme dans huit projets, on n'a pas identifié de raison indiquant que la qualité et la performance des revêtements RUMAC génériques réalisés par le procédé à sec, convenablement conçus et mis en place, ne pourraient être équivalentes à celles du mélange conventionnel d'asphalte équivalent produit à chaud (HMA). Ceci nécessitera une attention particulière à l'égard des facteurs suivants: sélection du type du composant CRM, compatibilité, granulométrie, composition et quantité du composant CRM; la méthode Marshall modifiée de conception des mélanges RUMAC; et la production, la mise en place et le compactage du matériau RUMAC lors de la réalisation du revêtement dans des conditions favorables. On doit noter que lors des comparaisons, la performance des mélanges de revêtement superficiel RUMAC à teneur relativement

élevée en gros agrégats CRM variait de très médiocre à médiocre. Pour cette raison, on a utilisé un matériau CRM plus fin (tamis 10 mesh, ou plus fin) à des concentrations d'addition de 1 à 1.5 pour cent dans beaucoup de projets plus récents de démonstration de l'utilisation du procédé RUMAC générique à sec.

Le procédé de production continue du produit AR par voie humide est très prometteur, selon les résultats des premiers tests (1977 à 1980) exécutés en Ontario et aux États-Unis (par exemple en Floride) et des tests actuels (section de test sur l'autoroute 400), et on devrait certainement poursuivre ces travaux d'évaluation. Il semble que le matériau AR peut améliorer la durabilité des mélanges d'asphalte denses ou contenant des cavités réalisés à chaud. Un État (Californie) a élaboré un guide intérimaire concernant le mélange d'asphalte caoutchouté à granulométrie sélective réalisé à chaud (ARHM-GG), incluant des équivalents de conception structurale plus mince. On devrait également envisager l'emploi du matériau AR dans les couches de friction denses ou contenant des cavités, dans les applications SAM et SAMI. En ce qui concerne l'emploi en Ontario du procédé humide de production continue du mélange AR, la meilleure méthode pourrait être le transfert de la technologie du ministère des Transports de Floride.

L'emploi du matériau CRM dans les projets de recyclage sur place à froid (RUMCIP) ne peut être actuellement considérée comme un succès technique du fait du niveau élevé de formation d'ornières et de séparation observé dans les deux projets de démonstration avant la mise en place de la surface d'usure conventionnelle HMA. On devrait évaluer cette technologie dans le cadre d'un programme d'évaluation fondamentale. Les analyses économiques n'ont pas été exécutées pour les projets RUMCIP.

Les résultats du projet (Thamesville, Phase II) impliquant le recyclage du matériau RUMAC générique (procédé à sec) (RRUMAC) et les résultats obtenus aux États-Unis par FHWA/EPA indiquent que le recyclage du matériau RUMAC ne pose pas de problème technique. Les résultats des études de FHWA/EPA indiquent également que le recyclage du matériau AR ne poserait pas de problème technique. Cependant, certaines questions demeurent au sujet de l'influence cumulative du recyclage répétitif des matériau RUMAC et AR sur la qualité des mélanges réalisés, et on devrait chercher les réponses à ces questions au moyen de tests en laboratoire et en usine. Bien que cela soit considéré improbable, s'il s'avérait qu'il ne soit pas possible de recycler des matériaux d'asphalte caoutchouté du fait de facteurs techniques ou du rapport disponibilité/demande, ceci entraînerait des coûts d'élimination significatifs.

Sur la base de l'expérience et des coûts en Ontario, il ne semble pas que l'utilisation du matériau RUMAC générique (procédé à sec) comme liant et revêtement superficiel de chaussée, par comparaison aux matériaux HMA conventionnels, soit économiquement réalisable, même si on tient compte de mesures d'incitation dans le cadre de la gestion des déchets. Compte tenu du peu de données disponibles concernant la performance à long terme, les résultats des analyses économiques sur la durée de vie des revêtements, pour les revêtements de matériau RUMAC générique réalisés à sec, ne peuvent être actuellement considérés que comme préliminaires.

On a effectué une analyse économique (coût sur la durée de vie) du matériau AR produit en continu par procédé humide, par extrapolation des résultats de tests réalisés aux États-Unis pour l'Ontario et pour des revêtements de chaussée typiques. S'il est possible, comme on le prévoit, de réduire les coûts d'entretien et/ou d'augmenter la longévité par incorporation de matériaux AR, cette utilisation de matériaux CRM offre certainement un potentiel d'économie considérable. C'est la position adoptée par les fournisseurs américains et plusieurs états aux États-Unis (par exemple: Arizona, Floride et Californie).

On a observé un chevauchement des résultats des tests de pollution de l'air, pour les procédés conventionnels HMA et RUMAC; les résultats manifestaient une grande variabilité, indiquant que, à l'exception du composé 4-méthyl-2-pentanone (également connu sous le nom de méthyl-isobutyl-cétone ou MIBK), il n'y avait pas de différence perceptible entre les rejets dans l'atmosphère des deux procédés. On pense que la grande variabilité observée est due aux pratiques d'exploitation de l'usine et d'entretien, et non pas à un effet imputable à l'emploi d'asphalte caoutchouté. Cependant, dans cinq des six projets de démonstration pour lesquels on a testé les rejets dans l'atmosphère, on a observé un rejet de MIBK au cours de la production du matériau RUMAC, tandis qu'on ne le détectait pas ou on le détectait en quantités très inférieures lors de la production du matériau HMA conventionnel. En quantité suffisante, le composé MIBK est un irritant de la peau et des muqueuses et il est modérément toxique par inhalation, mais n'est pas considéré comme cancérigène.

On a également observé un chevauchement des résultats obtenus lors des mesures de l'exposition des travailleurs pour les deux procédés; dans la plupart des cas, ces mesures étaient pour les composés concernés au niveau des limites de détection ou au-dessous. Les résultats des mesures de l'exposition des travailleurs étaient similaires pour les deux procédés impliquant les matériaux HMA conventionnels et RUMAC.

Aucun résultat n'a été obtenu en ce qui concerne la lixiviation des rebuts solides et la qualité des effluents pour l'asphalte caoutchouté. Bien qu'on considère que ces rebuts soient similaires à ceux des matériaux HMA conventionnels, ces questions demeureront en suspens jusqu'à ce qu'un travail de caractérisation soit entrepris pour ces procédés de production d'asphalte caoutchouté.

La technologie disponible de production d'asphalte, qu'il s'agisse des matériaux HMA conventionnels, RUMAC ou AR, est capable de satisfaire les critères de la réglementation de protection de l'environnement, sous réserve qu'elle soit conçue, gérée et exploitée d'une manière adéquate. Ceci est applicable aux rejets dans l'atmosphère, aux rebuts solides, aux effluents liquides et à l'exposition des travailleurs aux divers produits.

Les certificats d'approbation - air émis par le ministère de l'Environnement et de l'Énergie de l'Ontario pour les usines d'asphalte constituent un mécanisme de réglementation de la performance de l'industrie à l'égard de l'environnement. Actuellement, l'industrie de production d'asphalte considère le processus d'émission des permis comme restrictif, et considérerait que l'assujettissement des matériaux RUMAC ou AR à la procédure d'émission de permis entraverait la mise en oeuvre de ces matériaux. En vue de la résolution de ces questions, il conviendrait qu'on entreprenne en Ontario des discussions conjointes entre l'industrie et le gouvernement sur la technologie de l'asphalte caoutchouté et son application en Ontario.

On reconnait qu'il demeure nécessaire de résoudre certaines questions techniques afin d'optimiser l'application de la technologie de l'asphalte caoutchouté, et que d'autres travaux de développement seront entrepris dans certains domaines, comme la performance à long terme. Dans le cadre de ces travaux de recherche, lorsque c'est approprié, on ne devrait pas négliger l'aspect de la protection de l'environnement.

Plusieurs recommandations sont présentées à l'égard de la technologie de l'asphalte et de la protection de l'environnement, dans les domaines comme: sélection des matériaux CRM; mise en place du matériau RUMAC générique (procédé à sec); performance à long terme du matériau RUMAC; comparaisons économiques sur la vie du produit; élaboration continue du matériau AR (procédé humide); procédures de test pour les matériaux AR et RUMAC; influence du recyclage répétitif du matériau RUMAC; tests multiples des rejets dans l'atmosphère; problèmes d'odeur potentiels; et lixiviation des matériaux RUMAC recyclés et utilisés sur les chaussées. On suggère le concept de "centre d'excellence" et une interaction étroite avec FHWA aux États-Unis, en ce concerne l'application des recommandations concernant la technologie de l'asphalte. Il est important que les agences utilisatrices, l'Association ontarienne des constructeurs de routes, l'Association ontarienne des producteurs de mélanges d'asphalte à chaud, et les consultants en conception de chaussées soient tenus au courant et impliqués dans les activités de développement de l'utilisation des matériaux CRM dans les revêtements routiers d'asphalte en Ontario.

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EVALUATION OF RUBBER MODIFIED ASPHALT DEMONSTRATION PROJECTS

1. INTRODUCTION

1.1 BACKGROUND

Eleven Ontario rubber modified asphalt [1] demonstration projects were funded through the Ministry of Environment and Energy's (MOEE)[2] Tire Recycling Program, or completed by the Ministry of Transportation (MTO), between 1990 and 1992.[3] Thirteen additional rubber modified asphalt projects, from small to large (1,500 to 65,000 passenger tire equivalents), have been approved by the MOEE for the 1993 paving season (139,965 passenger tire equivalents), with further projects pending. The rubber modified asphalt demonstration projects are a part of the Province's medium-term scrap tire management strategy (Blackwell, 1992; MWR, 1992).[4]

JEGEL-ORTECH, working closely with the MOEE/MTO Rubber Modified Asphalt Demonstration Projects Review Committee, have prepared this report covering a comprehensive August to November 1993 study of the eleven demonstration projects. This study involved: evaluation of the eleven Ontario rubber modified asphalt demonstration projects in terms of materials and pavements factors, and environmental impacts, including recyclability; comparison of the findings to those of other jurisdictions, with identification of technical solutions to any issues; preparation of a summary of technically and cost-effective approaches to foster the use of rubber modified asphalt; and identification of policy and program impediments, with options for resolution. The integrated JEGEL focus on materials and pavements factors, and ORTECH focus on environmental impacts, is the broad scope of following Sections that address the MOEE's Terms of Reference study objectives.

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[1] See Appendix C for background on asphalt technology.

[2] See Appendix G for list of abbreviations.

[3] See Appendix B for demonstration project technical and environmental fact sheets.

[4] See list of References at the end.

1.2 OBJECTIVES

The MOEE/MTO Review Committee's objectives in evaluating the pavement performance and environmental impacts, including recyclability, of rubber modified asphalt are in many ways parallel to current United States Environmental Protection Agency (EPA) and United States Department of Transportation Federal Highway Administration (FHWA) activities related to the mandated recycling of scrap tire rubber (Bloomquist et al, 1993; FHWA/EPA, 1993; Lord, 1993). Section 1038 of the United States 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) addresses the study and use of scrap tire rubber by highway agencies. ISTEA mandates the use of recycled rubber from scrap tires for a minimum portion of any Federal-aid asphalt pavement projects: 5 percent for 1994; 10 percent for 1995; 15 percent for 1996; and 20 percent for 1997 and each subsequent year, noting that implementation has now been delayed for at least one year (Kane, 1993). However, the FHWA and EPA were also required to study and report on the pavement performance and environmental impacts of such use with Phase 1 recently completed (FHWA/EPA, 1993), and Phase 2 (unresolved engineering issues such as long term performance) to be completed in 1999 (Lord, 1993). As such, the FHWA and EPA Phase 1 reporting provides important comparative state-of-the-art information to this Ontario study, including the FHWA/EPA review of the MTO Thamesville Phase I and Haldimand-Norfolk Region Trial #1 projects.

The four objectives of this JEGEL-ORTECH study can be summarized as:

1. To comprehensively evaluate the Ontario rubber modified asphalt demonstration projects, and identify any outstanding pavement and environmental technical issues that impact on the timely implementation of the regular use of rubber modified asphalt in Ontario;
2. To compare the demonstration project results with similar work in other jurisdictions, and identify potential technical solutions developed for any outstanding pavement and environmental technical issues in Ontario;
3. To prepare a summary of technically and cost-effective approaches for the use of rubber modified asphalt (crumb rubber modifier) from the findings of the first two objectives, including aspects requiring additional study and propose elements for the design and implementation of a program to foster the use of rubber modified asphalt in Ontario; and

4. To identify policy and program impediments, if any, to the expanded use of rubber modified asphalt in Ontario.

Essentially, a comprehensive, comparative with state-of-the-art, pavement performance and environmental impacts evaluation of the rubber modified asphalt demonstration projects is required. This pavement performance and environmental impacts evaluation will be of assistance to the MOEE in developing and implementing policies and programs for the use of rubber modified asphalt. Pavement performance is obviously the key component in determining if a use of recycled rubber from scrap tires in asphalt paving is technically feasible and cost-effective. Environmental impacts during rubber modified asphalt production and placement, and recycling, will determine if such use is acceptable.

1.3 OVERVIEW OF ONTARIO DEMONSTRATION PROJECTS

The eleven MOEE/MTO 1990 to 1992 rubber modified asphalt demonstration projects included: eight rubber modified asphalt concrete (hot-mix asphalt) projects in which the one to three percent recycled rubber from scrap tires (termed crumb rubber modifier, CRM)[1]., introduced at the batch or drum plant (dry process), behaves essentially as a rubber aggregate with some modification of the asphalt cement (RUMAC), including one project with recycling of RUMAC placed the previous year (RRUMAC); two rubber modified cold in-place recycling (RUMCIP) projects in which three percent CRM acts essentially as unbound aggregate (no significant binding action); and one rubber modified asphalt cement (AR) project in which the 0.5 percent fine CRM (7 percent CRM blended into asphalt cement, wet process, acts essentially as asphalt rubber binder with improved temperature susceptibility properties. References for these eleven projects are given in Subsection 10.1 and their locations in Southern Ontario are shown in Figure 1.3.1.

It should be noted that there were Ontario AR trial sections (probably a very fine CRM ‘dry’ process) placed as early as 1976 (Fromm, 1981; George, 1976), and those sections placed by the Municipality of Metropolitan Toronto Transportation Department (Metro Transportation, MT) between 1977 and 1980 on major urban routes appear to be performing equivalent to, or somewhat better than, the overall system (JEGEL pavement management activities for Metro Transportation).

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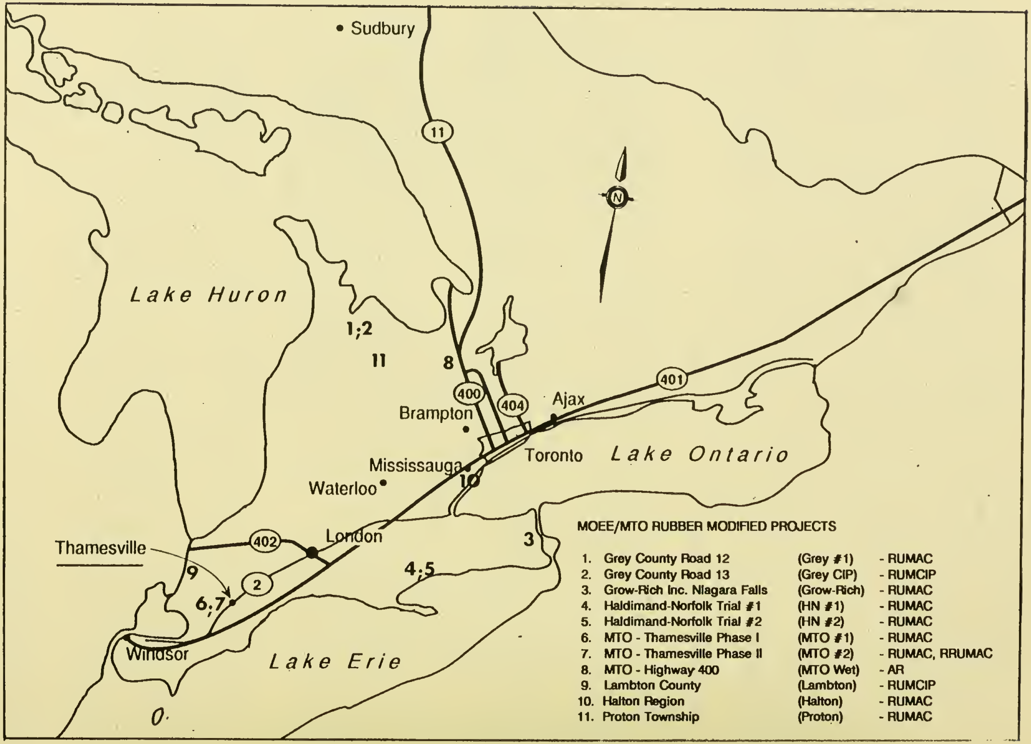
[1] See Appendix A for the terminology involved.

FIGURE 1.3.1 MOEE/MTO RUBBER MODIFIED ASPHALT DEMONSTRATION PROJECTS LOCATION MAP


Sudbury
11
N
Lake Huron
1;2
11
8
400
404
Ajax
401
Brampton
Toronto
Lake Ontario
Mississauga
10
Waterloo
London
402
Thamesville
9
2
6;7
4;5
3
Windsor
Lake Erie
MOEE/MTO RUBBER MODIFIED PROJECTS
1. Grey County Road 12 (Grey #1) - RUMAC
2. Grey County Road 13 (Grey CIP) - RUMCIP
3. Grow-Rich Inc. Niagara Falls (Grow-Rich) - RUMAC
4. Haldimand-Norfolk Trial #1 (HN #1) - RUMAC
5. Haldimand-Norfolk Trial #2 (HN #2) - RUMAC
6. MTO - Thamesville Phase I (MTO #1) - RUMAC
7. MTO - Thamesville Phase II (MTO #2) - RUMAC, RRUMAC
8. MTO - Highway 400 (MTO Wet) - AR
9. Lambton County (Lambton) - RUMCIP
10. Halton Region (Halton) - RUMAC
11. Proton Township (Proton) - RUMAC

2. RUBBER MODIFIED ASPHALT TECHNOLOGY

2.1 BACKGROUND

The use of recycled rubber from scrap tires (CRM) in asphalt did not develop as a solution to the solid waste management problems of scrap tire disposal and sustainable development (3Rs), or environmental problems such as stockpile fires (Moore and Miles, 1991). Construction materials engineers have worked for years with blending natural rubbers ('latex') and synthetic rubbers ('polymers') in asphalt cements (asphalt rubber binders) to enhance their rheological properties (Heitzman, 1992a.,b.). Tire rubber, generally a sophisticated blend of natural and synthetic rubbers, is an available raw material for such blending, in the form of tire buffings for instance (Rouse, 1993b.).

From the early 1960's, various proprietary and generic technologies have evolved for the use of recycled rubber from scrap tires (crumb rubber modifier, CRM) in asphalt rubber binder (AR) and rubber modified asphalt concrete (RUMAC). From the late 1980s, the emphasis for this wet and dry process technology has been on the potential as a solution to the solid waste management problems of scrap tires, which are generated at the rate of about one passenger tire equivalent per person per year. Each of these tires (9 to 10 kg) can, with appropriate processing, yield some 4 to 5 kg of CRM (Heitzman, 1992b.).

2.2 ASPHALT RUBBER BINDER AND RUBBER MODIFIED HOT-MIX ASPHALT

The material, process, technology and product schematic for CRM use in asphalt rubber binder (AR) and rubber modified hot-mix asphalt (RUMAC) is shown in Figure 2.2.1. There is some dry process interaction to modify the binder, as indicated by the dotted arrow lines, particularly for finer CRM and/or elevated mixing temperatures. The Ontario demonstration project focus has been on the dry process generic RUMAC.

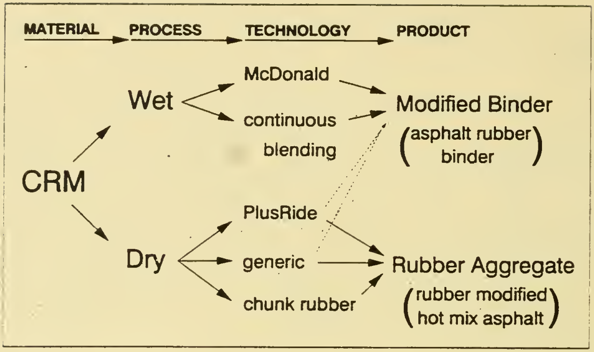


FIGURE 2.2.1 USE OF RECYCLED RUBBER FROM SCRAP TIRES (CRM) IN ASPHALT (Heitzman, 1992b.)

2.2.1 Crumb Rubber Modifier Production

There are four processes currently in use for producing CRM from scrap tire rubber: ambient grinding (crackermill process, No. 4 to 40 mesh)[1]; ambient granulating (granulator process, No. 4 to 30 mesh); cryogenic grinding (hammermill process, No. 4 to 100 mesh); and wet grinding (micro-mill process, No. 40 to 100 mesh) (FHWA, 1993b.; Heitzman, 1992a.). The principal source of raw material for producing CRM is scrap tire rubber delivered to the processing plant as whole tires, cut tire, shredded tire (preferred) and retread buffing waste (actually a byproduct). Quality control for CRM includes scrap tire feed stock quality, ash content, particle distribution and moisture content (Holland et al, 1992). Shipping of CRM can be in packages (typically 50 lb polybags on pallets) or in bulk. The pricing for CRM varies widely depending on processing logistics, volumes, packaging and particle size. Typical prices[2] for large volumes (100 tonnes CRM or more, typical of a medium sized asphalt paving project of 5000 tonnes hot-mix asphalt or more) FOB the CRM production plant, are: No. 4 mesh ($0.20 to 0.25/kg); No. 10 mesh ($0.25 to 0.30/kg); No. 30/40 mesh ($0.35 to

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[1] See Appendix F for metric conversions.

[2] Canadian dollars are used throughout, unless explicitly indicated otherwise.

0.45/kg); and No. 80 mesh ($0.45 to 0.55/kg) (FHWA, 1993b and JEGEL experience). These typical CRM prices will undoubtedly decrease in Ontario as more processing capacity for recycling scrap tire rubber is developed.

The US proponents of AR (International Surfacing, Inc., for example) have generally indicated that cryogenic process CRM is not suitable for this use, as compared to ambient CRM. Apparently the cryogenic process results in clean, flat surfaces with reduced reaction rates and lower elastic recoveries, as compared to the more reactive ambient process CRM sponge-like surface (Oliver, 1981; Roberts et al, 1989). The overall suitability and long-term performance of cryogenic process CRM for use in AR and RUMAC should certainly be evaluated for Ontario, as cryogenic process CRM has been used in several RUMAC projects, apparently with success.

2.2.2 Asphalt Rubber Binder

The McDonald method technology (original and ARM-R-Shield™, Ecoflex™, Flexochape™, Overflex™ and pressure reaction) and continuous blending method technology (Rouse UltraFine™, for instance) in Figure 2.2.1 are considered wet processes since the CRM is pre-blended (reacted) with the asphalt cement (sometimes extender oil and/or catalyst added) to ensure AR stability (complete dispersion) prior to being added to the heated aggregates in a batch or drum hot-mix plant or sprayed for surface treatment[1]. (ARPG, 1989; BAS, 1992; Bitumar, 1992; International Surfacing, 1992; Moreau, 1992; Morris, 1993; Page et al, 1992; Rouse, 1993a.,b.; Ruth, 1992; Sainton, 1990; Takallou and Sainton, 1992). The wet processes are well suited to all hot-mix plant operations since the CRM modifies the asphalt cement such that the AR can be added using the plant's asphalt cement system, subject to storage stability and somewhat increased pump wear. From an engineering and applications viewpoint, it would appear (MTO 1990 Highway 400 AR test section, for instance) that the wet processes are more economical, practical and predictable than the dry processes (Joseph and Kennepohl, 1991). The economics (life cycle costing) of AR use in hot-mix asphalt (HMA) are discussed in Subsection 4.4.

The use of AR in hot-mix asphalt (HMA) requires about 20 percent more asphalt rubber binder (ARB) than is used in comparable conventional hot-mix asphalt.

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[1] See Appendix A for more details on the technology involved.

However, the thicker films of ARB in the mix contribute to improved durability (particularly for open graded mixes) and with the ARB's lower temperature susceptibility, increased resistance to permanent deformation and thermal cracking (Estalehri et al, 1992; FHWA, 1993a.; International Surfacing, 1992; Krutz and Stroup-Gardiner, 1992; Lundy et al, 1993; Maupin, 1992; Raad, 1993; Roberts and Lytton, 1987; Sainton, 1990; Shuler and Estakhri, 1993). Asphalt rubber binders are used in stress-absorbing membrane (SAM) and stress-absorbing membrane interlayers (SAMI) to take advantage of their improved elastic recovery (BAS, 1992; International Surfacing, 1992; Rouse 1993a.).

2.2.3 Rubber Modified Hot-Mix Asphalt

The PlusRide^{TM} method technology (original Swedish RUBIT), generic method technology and chunk rubber technology in Figure 2.2.1 are considered dry processes since the CRM is mixed directly with the aggregate in a batch or drum hot-mix plant as a partial replacement of the mix aggregate in RUMAC. Care must be taken during the volumetric proportioning of the RUMAC to provide space in the matrix (voids) for the CRM, and enough additional asphalt cement to compensate for continuing absorption of asphalt cement (light ends) by the CRM particles over time (Amirkhanian, 1993; Eaton et al, 1991; Hansen and Anderton, 1993; Kandhal, 1993; Lundy et al, 1993; Rouse, 1993a.; Terrel et al, 1993).

If the CRM is fine enough (Rouse UltraFine^{TM} minus 80 mesh that has an 'average' size of 200 mesh, for instance), it can be incorporated in a bulk dry process by using the hot-mix plant's mineral filler system (system to feed filler into pugmill of batch plant or mixer section of drum plant, Figures C10 and C12[1].), which should prove more economical (Rouse, 1993b.). Rouse has introduced the CRM gradations into the FHWA CRM material, process, technology, product schematic (Figure 2.2.1) as shown in Figure 2.2.2 (Rouse, 1993b.).

2.3 DESIGN, PRODUCTION AND PLACEMENT

The mix design, production and placement of dry process, generic technology RUMAC is quite similar to conventional HMA. It does not appear that there is an overall manual of practice for RUMAC and RRUMAC and this should certainly be developed for the Ontario context. The stability of RUMAC mixes tends to be much

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1. See Appendix C for the asphalt technology involved.

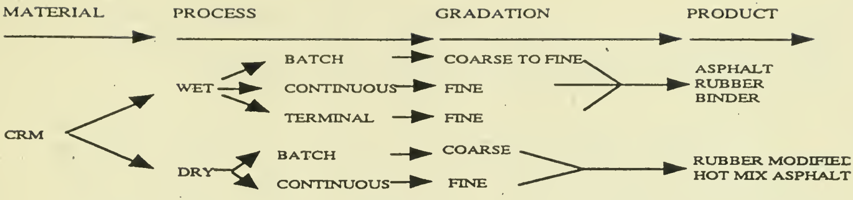

FIGURE 2.2.2 CRM RELATIONSHIP TERMINOLOGY (Rouse, 1993b.)

lower than comparable conventional HMA. At the mix design stage (Marshall method), it is important to recognize that the gradation of the selected aggregates must be adjusted volumetrically to accommodate the CRM (CRM bulk specific gravity of about 1.15 compared to about 2.6 to 2.7 for aggregates). A wider CRM size range, than the typical narrow sizing used presently (No. 10 mesh, for instance) in RUMAC, would most probably be technically better in terms of factors such as accommodation in the asphalt mix and maintaining more stability. This should certainly be considered in the continuing development of RUMAC technology.

The asphalt cement content of RUMAC will increase for the job mix formula (JMF), selected asphalt cement content and aggregate gradation over conventional comparable HMA by some 0.6 to 0.7 percent per percent CRM added (No. 10 mesh). As it appears that the CRM continues to absorb asphalt cement (light ends) with time, it is important to: 'temper' the mix for one hour before compacting briquettes in the laboratory; place a surcharge on the compacted briquettes to keep them from 'swelling' until cooled below 60°; and design a well asphalted mix (three percent air voids). Typically 2 to 3 percent CRM is being incorporated in binder course mixes and 1 to 2 percent in surface course mixes, noting the potential for low stabilities and high flows (tender mix) (FHWA, 1993b.).

The production of RUMAC is similar to conventional HMA, noting that additional dry mixing time is generally required for dispersion of CRM in a batch hot-mix plant. The CRM must be introduced after the asphalt cement in a drum hot-mix plant to avoid oxidizing the CRM or entraining it in the gas stream (Figure C13, for instance). It is important during transportation, placing and rolling to note that RUMAC is 'sticky' so that detergent type release agents are required in truck boxes and on rollers. Solvent based release agents must never be used with

RUMAC. Experience with rolling procedures is mixed, but generally only steel wheeled rollers are used, with care to avoid tearing and pushing the 'tender' RUMAC mat, and rolling is continued until the mat cools below 60°C.

The mix design, production and placement requirements for mixes incorporating 'McDonald' wet process technology (Figure 2.2.1) asphalt rubber binders (AR), such as stress absorbing membranes (SAM), stress absorbing membrane interlayers (SAMI), and asphalt rubber HMA (open-, gap- and dense-graded), have been established for some time and can be considered conventional asphalt technology (ARPG, 1989; International Surfacings, 1992).

The 'newest' wet process of continuous blending technology (Figures 2.2.1 and 2.2.2) (Rouse UltraFine^{TM}, for instance) has been evaluated by many states and Ontario (MTO Highway 400 AR test section). The Florida Department of Transportation (FDOT), based on extensive review, laboratory, placement and environmental studies, has developed comprehensive guidance for the use of continuous blending method AR in open- and dense-graded friction course HMA (FDOT, 1993; Page et al, 1992; Roberts et al 1989; Ruth, 1992). It should be noted that the continuous blending process may have to include a short additional reaction period to ensure adequate reaction of the CRM with the asphalt cement (Ruth, 1992).

A recent wet process fine CRM use in a rejuvenating agent for hot in-place recycling (RUMHIP) has been developed and demonstrated by Cutler Repaving (Cutler, 1992; Southwestern, 1992).

2.4 OTHER ASPHALT APPLICATIONS

While the focus on CRM use in asphalt is currently RUMAC and AR (RUMAC in Ontario), there is a wide range of other asphalt applications for recycled rubber from scrap tires, including: hot-poured rubberized asphalt joint sealing compound; hot applied rubberized asphalt water-proofing membrane; hot applied rubberized mastic water-proofing membrane; protection board; paving 'bricks'; and recreational asphalt surfaces (running tracks, for instance) (Beaty and Richards, 1993; Cassidy, 1990; Kearney, 1990; Kennepohl, 1993). Rubberized (CRM) asphalt joint sealant and water-proofing membrane is established and preferred materials technology in Ontario (JEGEL experience).

2.5 OTHER USES OF RECYCLED SCRAP TIRE RUBBER

A number of applications for recycled scrap tire rubber in transportation facilities construction have been developed or are being considered, including: lightweight embankment fill; erosion control blankets; insulation blankets (subgrade insulation); retaining walls; noise barriers; utility access hatch transition collars; energy attenuation; vehicle protection barriers; ballast for construction markers; portable speed bumps; and guiderail block-outs and ports (Anon, 1993; Berthelsen, 1989; Horner, 1993; Hughes, 1993; Humphrey and Eaton, 1993; Kearney, 1990; Kennepohl, 1993). Pavement insulation layer and lightweight fill applications for recycled scrap tire rubber are of particular relevance to Ontario given the relatively cold winter environment (frost penetration) and large areas of low strength foundation soils (muskeg, for instance).

2.6 PERFORMANCE

In order to review the performance of AR and RUMAC pavements determined by various highway agencies, with emphasis on RUMAC, the available information was checked through DIALOG^R (TRIS, EICOMPENDIX*PLUS, MATERIAL and RAPRA); requests for information to major agencies/contacts (Appendix F), JEGEL technical files, MTO technical files and direct experience/contacts (Aurilio et al, 1993; Baker, R., 1993; Baker, T., 1993; Dialog, 1991; EBA, 1993 (not for official release); Epps, 1993; Francois, 1993 a.,b.; Haughton, 1993; Justus, 1993; Kulash, 1993; Lord, 1993; Page et al, 1992; Rouse, 1993a.; Rugg, 1993; Steiner, 1993). This provided an excellent information base to consider along with the Ontario rubber modified asphalt demonstration projects discussed in Section 3.

It must be recognized that the question of mandated CRM use in the United States (ISTEA) is ‘controversial’, with somewhat divergent viewpoints being presented as to the pavement performance and environmental impacts, including recyclability (Flynn, 1993a.,b.; Kuennen, 1993). Regardless, it would now appear with the release of FHWA/EPA studies (FHWA/EPA, 1993), that the two remaining issues to resolve are: the ‘political’ mandating of CRM use in asphalt, even though this had been contemplated since 1986 (Federal Register, 1986); and more importantly, the long-term performance of AR and particularly RUMAC, that will undoubtedly require further study (FHWA Phase 2, for instance (Lord, 1993)). It is important to note that the FHWA/EPA studies included the MTO Thamesville Phase I and Haldimand Norfolk Region Trial #1 rubber modified asphalt demonstration projects. Also, there is far more practical experience with AR as compared to RUMAC, particularly the generic RUMAC technology adopted for the Ontario demonstration projects. Mandated CRM use in asphalt is not, of course, the case in Ontario.

Rather than simply paraphrasing the FHWA/EPA study findings with regard to the use of CRM in asphalt, it is worthwhile to quote the relevant pavement performance and recycling sections from their Summary and Conclusions, noting that the health/environmental assessment is the subject of Section 4 (FHWA/EPA, 1993; Bloomquist et al, 1993). Section 1038 (b) of ISTEA calls for the FHWA/EPA to conduct studies to determine the threat to human health and the environment, the recyclability, and the performance of asphalt pavement containing CRM. The mandated use of CRM may be delayed if reliable evidence indicates a threat to human health or the environment, difficulties occur in recycling the modified pavements, or the pavements do not perform adequately.

Performance

> "While pavements containing CRM have been constructed and have been in service for as many as 20 years in Arizona, California, and a few other States and based on an extensive review of available literature and project data, only limited information on engineering and economic performance is available. This is due to limited documentation, experimental evaluation, and a resulting incomplete data base upon which to conduct long-term performance evaluations. While other States have conducted limited experimental research with CRM technologies, the performance of asphalt pavements containing recycled rubber has received only limited evaluations under varied climatic and use conditions.
>
> In order to develop a reliable cost and economic evaluation of pavements containing CRM, comparable information must be developed on the construction of CRM asphalt paving projects of typical size rather than experimental applications. The performance to date on the CRM projects has been mixed, some experiencing early failure, others performing comparably to conventional asphalt pavements, and some CRM pavements have performed better than conventional mixes. Due to limited documentation, the exact cause of the premature distress in CRM pavements has not been established. However, when properly designed and

> constructed, there is no reliable evidence to show that pavements containing recycled rubber will not perform adequately as a paving material.
>
> We will continue national research on CRM technologies to develop reliable engineering and economic criteria for the CRM pavements. Additionally, many States are conducting coordinated research to evaluate the effects of local conditions and materials. The results of these studies will be included in long-term performance evaluations." (FHWA/EPA, 1993)

Recycling

> "Based on the results of two projects where asphalt pavements containing CRM were recycled, the available literature, and an evaluation of variability in plant configurations and operations, this technology appears to be constructible as a recycled pavement. To date, these two recycled pavements are performing comparably to existing hot mix asphalt pavement. However, sufficient information regarding long-term performance and economics is not available. These two projects represent an extremely limited perspective of the variability of in-service pavement properties, environmental conditions, varying asphalt cements and mixtures, and asphalt plant configurations and operations. However, there is no reliable evidence that asphalt pavements containing recycled rubber cannot be recycled to substantially the same degree as conventional HMA pavements.
>
> Additional evaluations are contemplated and will be required to develop further criteria for recycling CRM asphalt pavements. A national pooled-funds study has been initiated. Thirty-three States will participate with FHWA and EPA to further evaluate recycling of CRM pavements. Requests for proposals for this pooled-fund research effort will be solicited this fiscal year (1993)." (FHWA/EPA, 1993)

In summary then, the FHWA/EPA study state-of-the-art experience with the pavement performance and recyclability associated with CRM use in asphalt is:

1. When properly designed and constructed, there is no reliable evidence to show that pavements containing recycled rubber from scrap car tires will not perform adequately.
2. There is no reliable evidence that asphalt pavements containing recycled rubber cannot be recycled to substantially the same degree as conventional HMA pavements.

There are several factors to be noted regarding the performance and recycling information quoted from the FHWA/EPA study:

1. The economics (life cycle cost) of CRM use in AR and RUMAC were not considered.
2. The differences between AR and RUMAC were not considered in detail. It would appear that the experience with AR is generally more positive than indicated (Baker, T., 1993).
3. While there is some French evidence that AR mixes can be hot in-place recycled (porous asphalt rubber-concrete, Sainton, 1991)), direct JEGEL experience (April 1988, Goodyear Airport in Phoenix) indicates that a rubberized chip seal on top of HMA precludes hot in-place recycling unless the rubberized chip seal is first removed.
4. The issue of RUMAC reclaimed pavement (RUMAC-RAP) potential leachability was not addressed. However, there does not appear to be a problem in this regard from the available technical information (Thompson and Haas, 1992).

2.7 COSTS AND ECONOMICS

There is a paucity of documented cost data for CRM use in AR and RUMAC, and apparently the comparative economics (life cycle cost) with conventional HMA have not been considered. While it could be argued that the available long-term performance data for RUMAC are too limited for economic analysis, this is certainly not the case for AR.

Some interesting comparative initial cost data were obtained from both Rouse Rubber and AASHTO (Rouse, 1993a.; Steiner, 1993). Rouse Rubber considered the estimated cost of materials for a hot-mix friction-course (one inch) for eight comparable applications (Rouse, 1993a.):

	Case (Type of Asphalt Mix)	Cost per Square Yard for Materials Alone (US$)
1.	Conventional HMA, No Rubber, Base Case	1.02
2.	UltraFine^{TM} Rouse, Bulk Dry Process, Tire Rubber Powder	1.18
3.	Envirotire PlusRide, Dry Process, Tire Rubber Granules	1.76
4.	Generic, Dry Process, Tire Rubber Granules	1.57
5.	CRREL, Dry Process, Tire Rubber Chips	2.14
6.	Arizona (ISI), Wet Process, Tire Rubber Crumb	1.83
7.	UltraFine^{TM} Rouse, Bulk Wet Process, Tire Rubber Powder	1.18
8.	Polymer, Wet Process, SBR Latex Liquid	1.21

It should be noted that the percent CRM in each of the types of asphalt mix may be different and the cases presented may not be directly comparable because of the different material costs involved in each and the different performance expected from each.

The AASHTO 1993 survey of States for information on current CRM use in RUMAC and AR obtained comparative cost data that can be summarized as (Steiner, 1993):

	Average Cost/Ton (US$)	Number of Responses
Conventional		
Hot-Mix Asphalt (HMA)	27-29	39
Asphalt Cement (AC)	110	14
RUMAC		
CRM, No Patent	40-44	22
Increase over HMA	13-15	
(Percent Increase)	(50)	
CRM, Patented	53-58	25
Increase over HMA	26-29	
(Percent Increase)	(98)	
AR		
CRM, No Patent	346-394	5
Increase over AC	236-284	
(Percent Increase)	(236)	
CRM, Patented	416-458	12
Increase over AC	306-348	
(Percent Increase)	(297)	

There is no doubt that RUMAC and AR costs will decrease somewhat as CRM production capacity increases and RUMAC and AR technology becomes better established.

2.8 RESEARCH AND DEVELOPMENT NEEDS

A number of AR and RUMAC asphalt technology, pavement performance and recyclability research and development needs were identified during the review of the available technical information on CRM use in asphalt. These range from major research and development needs, such as the long-term performance of RUMAC pavements compared to conventional HMA pavements, to relatively minor such as guidance to contractors on the best placement and compaction procedure(s) for RUMAC. Obviously, before the long-term performance of RUMAC pavements is considered through laboratory performance testing (SHRP protocols, for instance (Kulash, 1993)), accelerated pavement testing and the monitoring of prototype pavement sections, the RUMAC must be properly designed and constructed (FHWA/EPA, 1993). The economics of AR and RUMAC use (life cycle costing) can only be determined when realistic long-term performance information is available. Technology transfer is a key element of this overall process, that should also consider appropriate waste management incentives, if any, to establish technically-sound, economically-attractive AR and RUMAC use.

The research and development needs identified include:

1. Determining the 'optimal' type (morphology, ambient or cryogenic), compatibility with asphalt cement (need for surface modification and/or adhesion additive), gradation (top size and grading band), composition (if a factor) and amount of CRM for a representative range of generic dry process RUMAC binder and surface course mixes. This should include a review of proprietary technology and/or patent impacts, if any. The mix designs and characterization should be based on SUPERPAVE^R Level 3 technology, or equivalent, and be fully documented.
2. Determining the most appropriate production (batch and drum hot-mix plants), placement and compaction techniques for a representative range of generic dry process RUMAC binder and surface course mixes. This technology should be fully documented.
3. Determining the long-term performance of the 'optimal' generic dry process RUMAC mixes, produced, placed and compacted with the most appropriate technology, through laboratory characterization (SHRP protocols), accelerated pavement testing and monitoring of the prototype pavement sections. This is essentially the current FHWA Phase 2 program on long-term pavement performance that will be completed in 1999 (Lord,

1993). Unfortunately, long-term performance monitoring does take time, even with thorough laboratory characterization and accelerated testing. It is critical that the monitoring program will yield the necessary data and information (SHRP LTPP for instance (SHRP, 1990)).

4. Using the generic dry process RUMAC long-term performance data, as they become available, in economic comparisons (life cycle costing) with conventional asphalt concrete (HMA) pavements.
5. Evaluating the wet process continuous blending of AR (Rouse, 1993a.; Ruth, 1992) in terms of fine CRM, AR production and AR use in a range of HMA surface and binder course mixes (Florida uses in dense- and open-graded friction courses). The necessary wet process continuous blended AR design, specification and construction technology guidance should be developed and documented. This will undoubtedly be similar to the established 'McDonald technology' for AR use in HMA, and draw heavily on Florida friction course and California gap-graded hot mix experience with AR. California use of asphalt rubber hot mix gap-graded (ARHM-GG) is considered non-experimental and they have developed an interim guide, which includes thinner structural design equivalents than conventional HMA, that is FHWA 'approved' (FHWA, 1993a.). Reduced AHRM-GG thicknesses, with comparable performance to HMA, are very important to life cycle costing advantages.
6. Reviewing the available AR pavements information (SAM, SAMI and dense- and open-graded HMA) to check the long-term performance. With the number of AR projects completed over the last thirty years (including Metro Toronto Transportation), it should be possible to provide realistic long-term performance and economics (life cycle costing) information. This would obviously be supplemented by the evaluation of wet process continuous blended AR.
7. Evaluating the available test procedures for AR and RUMAC quality control and quality assurance. The necessary technical guidance should be developed and documented, as it does not appear to be available even in current design guides (Heitzman, 1992a).
8. Determining, through laboratory evaluations (asphalt cement and mix properties), the overall effects on RUMAC quality of repeated recycling. This should also be checked through repeated RRUMAC production in batch and drum hot-mix plants.

9. Determining, through field evaluations, the technical acceptability and environmental impacts of hot in-place recycling of RUMAC and AR pavements.

It is recognized that this list of pavement performance research and development needs is probably not inclusive and does reflect some 'frustration' that the time available for the FHWA/EPA study was clearly not adequate for the task at hand (FHWA/EPA, 1993).

An important AR initiative is the current Transportation Association of Canada (TAC) research project, supported by the MOEE, on the wet process use of depolymerized CRM in asphalt cement.

3. TECHNICAL REVIEW OF ONTARIO DEMONSTRATION PROJECTS

3.1 BACKGROUND AND PERFORMANCE MONITORING

The available reports on the eleven Ontario rubber modified asphalt demonstration projects (Subsection 10.1 of References) were supplemented by JEGEL site visits to each project during September, 1993, to both complete pavement condition evaluations (Chong et al, 1989a.,b.) and review the information with the project engineers[1]. A video covering the main site visit observations has been provided to the MOEE, that also includes an overview (November 1989) of the Metro Toronto Transportation AR trial sections placed between 1977 and 1980.

It should be noted at the outset of any technical review of the MOEE/MTO 1990 to 1992 CRM demonstration projects that, in common with most agencies, this was at a very early 'leading edge' stage on the appropriate CRM asphalt technology 'learning curve' for several reasons: generic dry process RUMAC materials selection, mix design, production, placement and testing requirements were, and are, still being developed, documented and implemented (FHWA will be completing their Phase 2 CRM engineering study in 1999, for instance); while the 'McDonald technology' for AR is well established, the generic wet process continuous blending technology for AR has only recently been established (Florida, for instance) with the necessary blending equipment for terminal or hot-mix plant production now readily available; the use of CRM with cold in-place recycling (RUMCIP) appears to be unique to Ontario; and Ontario has been a leader in using cryogenic process recycled scrap tire CRM. Clearly, it is important to learn from this leading edge MOEE/MTO experience in order to incorporate appropriate CRM asphalt technology in future CRM asphalt paving projects. This is the focus for the technical review.

Technical and environmental project summary fact sheets were prepared for each rubber modified asphalt demonstration project, including the pavement condition, as given in Appendix B. Unfortunately, considerable information was left out of the documentation for almost every project: hours of plant operation; design life of pavement; information on aggregates (percent crushed, petrographic number, Micro-Deval loss and quality control); information on CRM (moisture content and chemical properties); details on trucks, paver and rollers; smoothness of pavement; hot mix production (materials usage and observations); costing data (unit costs, costs for quality control and quality assurance, and costs for plant modifications, incorporating CRM and emission controls; monitoring of tire-pavement noise levels (Sandberg et al, 1990); and monitoring of winter snow and ice development and its control. Improved ice control has been claimed to be an advantage of RUMAC (PlusRide^{TM}).

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[1] See Appendix F for list of key contacts.

It is recommended that the monitoring of winter snow and ice development, and its control, be implemented this winter for the RUMAC and RUMCIP demonstration projects. This can probably be best accomplished by the patrol staff keeping notes on observed differences in appearance and salt/sand use for the RUMAC and RUMCIP sections, as compared to control sections. The frictional properties (spring and fall) should be monitored for all of the demonstration projects in 1994, recognizing that the RUMCIP sections have a wearing surface (HL 4) on top of the cold in-place recycled material. Rather than continuing somewhat sophisticated and expensive performance monitoring procedures such as deflection testing on some of the demonstration projects, it is recommended that an overall visual performance assessment of all the demonstration projects be completed in the spring and fall by a qualified pavements engineer. This will provide cost-effective continuing pavement performance information so that the current conclusions and experience can be properly extended.[1].

It should also be noted that the agency contacts involved during the site visits were most interested in the performance monitoring and its impact on future CRM asphalt technology, and prepared to continue with CRM demonstration projects that were technically-sound, and particularly, economically-attractive to the agency.

3.2 PROJECT PROFILES - TECHNOLOGY AND APPLICATION

The rubber modified asphalt demonstration project profiles, in terms of technology and application, are summarized in Table 3.2.1. Environmental aspects of the projects are covered in Section 6. The asphalt technology and pavement

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1. A general guide for the development and monitoring of major CRM asphalt paving demonstration projects is given in Appendix E. For general CRM asphalt paving projects, annual visual performance monitoring is recommended to supplement the testing and monitoring associated with conventional asphalt paving projects.

performance aspects are discussed in following Subsections. As noted, Ontario is near the beginning of the 'learning curve' for CRM use in asphalt paving, particularly with the generic dry process RUMAC, so that care must be taken in reaching conclusions or extending the short-term performance experience to anticipated long-term performance.

3.3 MATERIALS AND MIX DESIGNS

The eight RUMAC (one also with RRUMAC, MTO #2), two RUMCIP and one AR demonstration projects summarized in Table 3.2.1 incorporated a wide range of CRM types (ambient and cryogenic), gradations (No. 4, 10, 20 and 80) and contents (1 to 3 percent). Given the availability of cryogenic process CRM in Ontario, it is important that any questions concerning its technical suitability for use in AR or RUMAC be resolved as outlined in Subsection 2.8. Ontario appears to be a leader in the use of cryogenic process CRM, and no apparent differences from ambient process CRM have been noted in the demonstration project reports. However, a direct comparison of cryogenic process CRM with ambient process CRM has not been made for the same RUMAC mix design, production and placement.

The performance of surface course RUMAC incorporating fairly coarse CRM (No. 4 mesh) appears to be poor, with extensive ravelling, considerable pop-outs and poor longitudinal and transverse joints (MTO #1 and HN #1, for instance). The RUMAC surface course performance appears to have been improved by incorporating No. 10 mesh CRM at a lower addition level of 1.5 percent (Grey #1 and HN #2, for instance), but this is again a short-term observation that may also reflect other factors such as better paving conditions. Regardless, it is important that the most appropriate CRM type, grading, composition and content, and CRM compatibility, be established for typical RUMAC binder and surface courses as outlined in Subsection 2.8. It must be recognized that space must be made available for the CRM in the asphalt mix matrix by volumetrically re-proportioning the aggregates. This is a difficult proposition unless the CRM grading is similar to one of the fine aggregate gradings or the combined fine aggregate grading.

It is important that special aspects of the Marshall method of mix design for RUMAC, such as oven tempering of the mix prior to briquette compaction, to allow for asphalt cement absorption, be documented and overall AR and RUMAC design guidance provided.

TABLE 3.2.1 SUMMARY OF MOEE/MTO RUBBER MODIFIED ASPHALT DEMONSTRATION PROJECTS

PROJECT AND LOCATION[1]. IDENTIFICATION[2]./TIRES[3].	DATE	PROCESS[4]. MIX TYPE	CRM PERCENT TYPE	PLANT FUEL CONTROL SYSTEM	'COMPARATIVE' PAVEMENT PERFORMANCE	ENVIRONMENTAL MONITORING
Grey County Road 12 Grey #1 33,000	Nov./91 May/92	RUMAC HL 4	1.5 Ambient, No.10	Batch Oil Dry	Similar (Very Good) Poor Areas[6].	Yes[5].
Grey County Road 13 Grey CIP 7,000	Aug./92	RUMCIP CIP	2 Cryogenic, No.4	CIP Process Not Applicable	Under Surface Course Similar (Excellent) Initial Problems	Not Applicable
Grow-Rich Inc. Niagara Falls Grow-Rich 16,000	Nov./92	RUMAC HL 8, HL 3	1.75, 1.75 Cryogenic, No.10, No.20	Batch Gas Dry	Covered by Pile Apparently Good No Control	Yes
Haldimand-Norfolk Trial #1 HN #1 78,000	Oct. to Nov./90	RUMAC HL 8, HL 3	3, 2 Ambient, No.4	Batch Oil Dry	Very Poor (Poor) Poor Areas	Yes
Haldimand-Norfolk Trial #2 HN #2 60,000	Aug./92	RUMAC HL 8, HL 3	3, 2 Cryogenic, No.10	Batch Oil Dry	Similar (Very Good)	Yes
MTO - Thamesville Phase I MTO #1 31,100	Oct./90	RUMAC HL 4	2 Ambient, No.4	Drum Oil Wet	Very Poor (Fair) Ravelling Pop-outs	Yes Comprehensive
MTO - Thamesville Phase II MTO #2 26,500	Oct./91	RUMAC RRUMAC HL 4	2 Ambient, No.10	Drum Oil Wet	Somewhat Poor to Similar (Very Good)	Yes Comprehensive
MTO - Highway 400 MTO Wet Not Known	July/90	AR HL 4, HL 1	0.5 (7 of AC) Ambient, No.80	Drum Gas Dry	Good (Excellent) 50 Percent Less Transverse Cracking	No

TABLE 3.2.1 (Continued)

PROJECT AND LOCATION[1]. IDENTIFICATION[2]./TIRES[3].	DATE	PROCESS[4]. MIX TYPE	CRM PERCENT TYPE	PLANT FUEL CONTROL SYSTEM	'COMPARATIVE' PAVEMENT PERFORMANCE	ENVIRONMENTAL MONITORING
Lambton County Lambton 16,000	July/92	RUMCIP	3 Cryogenic, No.4	CIP Process Not Applicable	Under Surface Course (Excellent) No Control Initial Problems	Not Applicable
Halton Region Halton 37,000	Aug. to Sep./92	RUMAC HL 8, HL 3	1.5, 1.3 Ambient, No.10	Batch Gas Dry	(Excellent) No Control Little Traffic to Date	No
Proton Township Proton 7,000	May/92	RUMAC HL 4	1.0, 1.5 Ambient, No.10 (From Grey #1)	Batch Oil Dry	Similar (Very Good) 85/100 and 150/200 Used	No

Notes:

1. See Figure 1 for projects location map.
2. Abbreviations for project identification, Subsection 12.1 of References.
3. Passenger tire equivalents used.
4. RUMAC - rubber modified asphalt concrete (hot-mix asphalt)
   RUMCIP - rubber modified cold in-place recycling
   RRUMAC - recycled RUMAC
   AR - asphalt rubber (rubber modified asphalt cement, AC)
5. Details in Section 6 and Appendix B.
6. Details in Section 3 and Appendix B. 'Comparative' is for September, 1993, overall assessment. General condition is given in brackets (Very Good, for instance). For example, for Haldimand-Norfolk Trial #1 (HN #1), the RUMAC HL 3 section's comparative performance to the control HL 3 section is very poor, while the general condition of the RUMAC HL 3 section itself is poor.

The design of RUMCIP mixes follows the Oregon Department of Transportation experience which should be checked for overall applicability with CRM addition, given the initial rutting problems experience with RUMCIP.

3.4 EQUIPMENT

There do not appear to have been any significant difficulties at batch or drum hot-mix plants with incorporating the CRM[1]. However, care must be taken with poly-melt bags to ensure they are fully melted and mixed in. It is not clear how much additional dry mixing time is required for batch hot-mix plants to incorporate CRM, particularly finer CRM, if any.

3.5 PRODUCTION AND PLACEMENT

It appears that the production of RUMAC and AR generally went smoothly, with the only significant placement problems associated with compaction of the somewhat tender RUMAC mixes, and the propensity for rubber tired roller pick up with the 'sticky' mixes involved. These are certainly somewhat experience related problems, but the question of whether rubber tired rollers should be used at all with RUMAC should be resolved. Practical production, placement and compaction guidance for RUMAC should be developed in conjunction with contractor groups such as the Ontario Hot Mix Producers Association (OHMPA).

There were rutting problems associated with the placement of RUMCIP and the efficacy of this CRM use must be critically assessed. It is not clear how the simple addition of CRM to cold in-place recycling can improve the process or the subsequent pavement performance. The use of cold in-place asphalt recycling is growing in Ontario as a method of mitigating reflection cracking (Grey County, for instance). It is important that the overall quality of cold in-place asphalt recycling be maintained to foster its use.

3.6 QUALITY CONTROL AND QUALITY ASSURANCE

There were many quality assurance results to review and summarize. These quality assurance summaries are generally given in Appendix B in terms of RUMAC job mix formula (JMF) requirements and RUMAC production range (minimum and maximum). There do not appear to be any significant problems in producing AR and RUMAC to the JMF (asphalt cement content, aggregate gradation and physical properties), but it is difficult with AR and RUMAC to accurately determine the asphalt cement content and complete conventional viscosity testing. Any necessary 'viscosity' testing of AR or properly recovered asphalt cement from RUMAC could be completed using a rheometer and this is not presently an issue for quality assurance testing. The monitoring of asphalt cement content in RUMAC requires pre-testing to establish the amount of CRM that effectively becomes an asphalt cement component (some 10 to 20 percent), and must be adjusted for in conventional solvent based extraction methods. The use of nuclear asphalt cement gauges has proven most promising (HN #2, for instance) provided proper calibration for the RUMAC is completed and the RUMAC is fairly consistent. Again, technical guidance on AR and RUMAC testing should be documented.

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[1] See Appendix C for details on batch and drum hot-mix plants.

3.7 PROBLEMS AND RESOLUTION

The 'tender' and sticky mix problems with the compaction of RUMAC were indicated in Subsection 3.5, and have been a common problem with other agencies. These have been resolved through care during initial compaction to avoid pushing and shoving and the use of detergent based release agent. The workability problem of RUMAC should also be considered at the mix design stage to ensure adequate stability is being provided.

While experience with AR is limited (MTO Wet), there should be no problems beyond placing and compacting a sticky mix, and contractors have had considerable experience with placing and compacting similar sticky polymer modified HMA.

There were no obvious problems during the processing stage of RUMCIP (Grey CIP and Lambton), however, in both cases extensive rutting and ravelling of the cold in-place recycled material were experienced after being subjected to traffic. For the Grey CIP, this was resolved by reprocessing with additional emulsion and a remedial overlay, while for Lambton this was resolved by reprocessing with additional emulsion. As indicated previously, the continuing use of RUMCIP must be critically reviewed. It should be noted that the RUMCIP is actually covered by a conventional HMA wearing surface so that direct observation of the RUMCIP is not possible.

3.8 PERFORMANCE OF PAVEMENTS

The relative short-term performance of the one wet process continuous blending AR project (MTO Wet) has been good in comparison to the control section, with the AR section in excellent condition and 50 percent less transverse cracking. This favourable performance would generally be anticipated from polymer modified HMA experience. Regardless, wet process continuous blending AR should receive more attention as indicated in Subsection 2.8.

The initial performance of the two RUMCIP projects was poor and should probably have been anticipated from the available information on cold in-place recycling with emulsions.

The relatively short-term performance of the RUMAC (surface course) projects has been quite mixed but two performance groupings, in comparison to control sections, can be distinguished:

1. Very Poor - RUMAC surface course typically incorporating 2 percent No. 4 mesh CRM (HN #1, MTO #1 and to some extent MTO #2) and involving late paving season placement.
2. Similar - RUMAC surface course typically incorporating 1.5 percent No. 10 mesh CRM (Grey #1, HN #2, Halton and Proton) and involving reasonable paving season placement.

These observations clearly support the FHWA/EPA conclusion that properly designed and constructed RUMAC pavements will perform adequately (FHWA/EPA, 1993). It should be noted that these are short-term performance considerations, and the key issue of long-term RUMAC performance remains to be addressed for the Ontario demonstration projects. The planned monitoring programs to 1996 for these RUMAC projects will not be adequate for assessing the comparative long-term performance as conventional HMA surface course typically lasts for fifteen years between resurfacings.

3.9 COST

Economic analyses (life cycle costing) have been developed for RUMAC and AR from available conventional HMA information and CRM addition incremental costs. These economic analyses are given in Section 4.

4. ECONOMIC ANALYSIS

4.1 GENERAL

In order to evaluate the economic benefits (or disbenefits) of Ontario RUMAC and AR pavements, a comprehensive economic analysis of conventional HMA, generic dry process RUMAC and AR asphalt pavements was completed, including sensitivity evaluations. The economic analysis focus is on RUMAC, as there is little current Ontario information available on wet process continuous blending AR, with the exception of the MTO 1990 Highway 400 AR (Rouse Ultrafine^{TM}) test section (Joseph and Kennepohl, 1991). However, Rouse has provided fairly detailed comparative US costing data for wet process continuous blending AR that appear to be appropriate in the Ontario context (Rouse, 1993a.).

There are a number of items to consider when assessing the short and long term economic impact of an innovative material such as generic dry process RUMAC, including equipment requirements, serviceability and performance factors, 'political' concerns and materials costs. Equipment requirements include: any plant or equipment modifications necessary to meet environmental or production requirements; operating costs; maintenance costs; and effect (reduction in particular) on production. Serviceability and performance factors encompass such items as the relationship between any increment in costs and pavement performance; the effect of pavement salvage value on life cycle costs; the quantity of recycled wastes to be used; and the recyclability of HMA containing wastes or byproducts. Political concerns include items such as whether or not incentives should be provided for materials incorporating recycled wastes and if the waste generators should offer incentives to the highway construction industry to encourage use of the waste. Materials cost issues are somewhat more straightforward and include any increment in materials costs necessary to incorporate the waste into HMA, such as an increase in asphalt cement required, supply of CRM, additional aggregate requirements, etc. Each of these factors was evaluated as part of the overall economic assessment of generic dry process RUMAC pavements. This assessment also includes consideration of the sensitivity of the analysis to various input parameters; for instance, what is the consequence of a lower CRM price on the overall economic analysis of RUMAC use?

4.2 INITIAL COSTING ASSUMPTIONS FOR RUMAC ECONOMIC ANALYSIS

An initial cost comparison of conventional HMA and generic dry process RUMAC was completed as the first component of the economic analysis. It should be noted that there are minor additional costs (RUMAC mix design and quality assurance costs more than HMA, for instance) and cost savings (RUMAC has 2 to 4 percent more yield than HMA as lower bulk relative density, for instance), that tend to offset, and have not been considered.

Three very important assumptions have been made throughout the economic analysis: the cost of the disposal of RUMAC, in the event that it can not be recycled for supply or technical reasons, has not been included; the inherent energy content of scrap tires has not been considered; and the incentives to use recycled scrap tire rubber are hypothetical only to show life cycle cost impacts.

From an equipment point-of-view, generally no significant environmental or production modifications are involved. The CRM feed systems are quite conventional, particularly for hot-mix batch plants. However the Certificate of Approval - Air for the hot-mix asphalt plant must be extended to cover the production of RUMAC. There are some additional staff and equipment requirements, including workers (at least two) to load the CRM into the plant, and a loader and operator to handle the pallets of CRM. The HMA production rate is not affected if a hot-mix drum plant is involved. If a hot-mix batch plant is used, some reduction in production can be experienced in order to ensure that the CRM is effectively distributed through the mix.

The materials requirements for RUMAC are relatively straightforward: for each 1 percent of CRM incorporated in RUMAC, the asphalt cement content increases by about 0.6 percent, based on practical experience. Therefore, if a conventional HL 3 mix has an asphalt cement content of 5.0 percent, a comparable HL 3 RUMAC mix with 1.5 percent CRM and the same aggregates (volumetrically adjusted fine aggregate proportions to accommodate CRM) will require an asphalt cement content of about 5.9 percent. The cost of the individual materials is therefore a major component of the economic analysis. The current price of No. 10 mesh CRM is about $ 300./tonne plus about 10 percent delivery in the Greater Toronto Area (GTA), with asphalt cement currently costing $ 150./tonne plus about $ 10/tonne delivery in the GTA. While the price of asphalt cement is expected to remain relatively stable, the cost of processed CRM should decrease as RUMAC and AR use increases.

Consequently, for the economic analysis of RUMAC, JEGEL have evaluated the cost implications of CRM at $ 330./tonne and $ 220./tonne. A $ 1./tonne of hot mix increment for handling the CRM at the plant and 15 percent mark-up (industry standard practice) on the RUMAC have also been included.

While incentives are currently not offered for the use of recycled scrap tire rubber (CRM) in RUMAC, some consideration has been given to the 'value' of the potential savings in disposal costs due to the use of scrap tires. Approximately 50 to 60 percent of a scrap tire is recovered through processing for CRM (the average tire mass is about 9 kg, and 5 kg of CRM can be produced from each tire). Consequently, about 5 kg of scrap rubber for each tire is diverted from disposal. At the current disposal fee of about $ 100./tonne in the GTA, an HL 3 RUMAC mix containing 2 percent CRM represents about a $ 2./tonne of hot mix 'saving' in disposal costs. As disposal costs have varied somewhat recently, are dependent to some degree on the location (GTA typically more expensive than other areas of Ontario) and there are 'societal' factors, a range of incentives has been assumed for the economic analysis ($ 50./tonne, $ 100./tonne and $ 200./tonne), and of course the base line case of no incentive.

The following parameters were included in the initial cost comparison of conventional HMA and RUMAC mixes:

Mix Types:
HL 3 HMA (current price of about $34.00/t[1] in GTA)
HL 8 HMA (current price of about $25.00/t in GTA)
HL 3 (1.5% CRM) RUMAC (requiring 0.9 percent additional AC)
HL 3 (2.0% CRM) RUMAC (requiring 1.2 percent additional AC)
HL 8 (2.0% CRM) RUMAC (requiring 1.2 percent additional AC)
HL 8 (3.0% CRM) RUMAC (requiring 1.8 percent additional AC)

Asphalt Cement Price: $ 150./t plus $ 10./t delivery in GTA

CRM Price:
$ 300./t plus 10 percent delivery in GTA ($ 330./t total)
$ 200./t plus 10 percent delivery in GTA ($ 220./t total)

CRM Addition at Plant: $ 1./t of hot mix, plus 15 percent mark-up

Incentive for Scrap Tires:

		CRM Addition Rate		
Incentive		1.5 %	2.0 %	3.0 %
None		0	0	0
$ 50./t	of CRM	$ 0.75/t	$ 1.00/t	$ 1.50/t of CRM
$ 100./t	of CRM	1.50/t	2.00/t	3.00/t of CRM
$ 200./t	of CRM	3.00/t	4.00/t	6.00/t of CRM

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[1] t = tonne in columns and tables.

An initial cost comparison of conventional HMA mixes and RUMAC mixes, based on the above parameters, is presented in Table 4.1. An example cost calculation for an HL 3 (1.5 % CRM) RUMAC mix is as follows:

HL 3 Cost =	$ 34.00		
CRM (1.5 %) @ $ 330./t =	4.95	@ $ 220./t =	$ 3.30
Additional AC (0.9 %) @ $ 160./t =	1.44		
Labour Cost to Add CRM to Mix =	1.00		
15 % Mark-Up on Additional Items =	1.11		0.86
	$ 42.50		$ 40.60
Less Incentive ($50/t rate) =	0.75		0.75
Total:	$ 41.75		$ 39.85

TABLE 4.1 INITIAL COST COMPARISONS OF CONVENTIONAL AND RUMAC MIXES

MIX TYPE	PRICE/TONNE			
Incentive for Use of Scrap Tires (Per tonne of CRM)	0 (No Incentive)	$ 50.	$ 100.	$200.
HL 3 (Conventional)	34.00			
HL 3 (1½%) RUMAC (0.6% AC/1% CRM) CRM @ $ 300/t + $ 30. Del.	42.50	41.75	41.00	39.50
CRM @ $ 200/t + $ 20. Del.	40.60	39.85	39.10	37.60
HL 3 (2%) RUMAC (0.6% AC/1% CRM) CRM @ $ 300/T + $ 30. Del.	44.95	43.95	42.95	40.95
CRM @ $ 200/t + $ 20. Del.	42.42	41.42	40.42	38.42
HL 8 (Conventional)	25.00			
HL 8 (2%) RUMAC (0.6% AC/1% CRM) CRM @ $ 300/t + $ 30. Del.	34.92	33.92	32.92	30.92
CRM @ $ 200/t + $ 20. Del.	33.42	32.42	31.92	29.92
HL 8 (3%) RUMAC (0.6% AC/1% CRM) CRM @ $ 300/t + $ 30. Del.	40.92	39.42	37.92	34.92
CRM @ $ 200/t + $ 20. Del.	37.05	35.55	34.05	31.05

Based on the initial cost comparison figures presented in Table 4.1, the conventional HMA mixes are less costly than the RUMAC mixes regardless of the incentive selected to account for disposal 'savings'. At the most optimistic, RUMAC is still about 15 to 20 percent more costly than conventional HMA. If no incentive is attributed to RUMAC and CRM prices remain at their current relatively high level, the RUMAC mixes are approximately 32 to 39 percent higher in initial cost than equivalent conventional HMA mixes. These initial first cost comparisons are similar to those suggested from recent United States RUMAC experience (Francois, 1993a.; Rouse, 1993a.).

4.3 LIFE CYCLE COST ANALYSIS FOR RUMAC

4.3.1 Life Cycle Cost Analysis Procedure

To evaluate essentially equivalent pavement alternatives involving alternate materials, it is necessary to consider not only the initial cost of each alternative but also the total cost over its service life. The alternative having the lowest initial cost may not represent the most practical alternative once factors such as maintenance, rehabilitation and inflation (and in contrast, the value of money invested today for future use, i.e. interest) are taken into account. The most effective method of measuring the cost-effectiveness of alternative designs is life cycle cost analysis.

There are a number of life cycle cost analysis approaches that could be employed to evaluate construction materials, however, the most appropriate method appears to be that recommended by Kerr and Ryan (Kerr and Ryan, 1987) which has been utilized by MTO and The Asphalt Institute (AI). This method of measuring the cost-effectiveness of pavement alternatives equates present and future expenditures for each alternative, and associated maintenance and rehabilitation costs, by taking into account both inflation and interest rates over the life of the project. The concept of present value or 'discounting' is used to permit comparison of alternatives that require expenditure over an extended period of time, which allows the designer to consider the dual effects of interest rates (the time value of money) and inflation on project cost.

While there may be large differences between interest rates and inflation rates from time to time (about 11 percent in 1986 for instance), interest rates and inflation rates tend to interact and influence each other so that they move together within a relatively narrow range over an extended period of time. The interest rate will reflect the cost of borrowing for the agency undertaking the project. For example, government agencies can usually finance a project at a lower rate than private agencies that generally have to borrow money at or near the prime lending rate. Despite the occasional relatively large apparent differences between interest and inflation rates, historically the 'discount' rate, or the real difference between interest and inflation rates over an extended period of time (thirty years), has been reported by Kerr and Ryan to be generally about 3 to 4 percent for privately financed projects (1 to 3 percent for US state and federal agency financed projects). These figures are consistent with those recently projected by Canadian financial institutions such as the Royal Bank of Canada[1]. In addition, recent provincially sponsored major transportation projects have assumed a long-term yield on Government of Canada bonds of 7.5 percent. Therefore, an interest rate of 7.5 percent has been assumed for the life cycle costing of RUMAC pavements, and an average inflation rate of 4 percent over the design life of the pavement, which results in a discount rate of 3.5 percent.

The service life of each alternative must also be taken into consideration for equivalent life cycle cost comparisons. A conventional asphalt concrete pavement usually requires a major overlay after about 15 years to extend its functional service life. The timing for major maintenance and rehabilitation treatments required for each alternative must be taken into account and the most appropriate service life selected for life cycle cost analysis. For instance, the functional service life of an asphalt concrete pavement without major rehabilitation is about 25 years.

4.3.2 HMA and RUMAC Life Cycle Cost Comparisons

Comparative life cycle cost analyses of generic dry process RUMAC and conventional HMA mixes are presented in Table 4.2. In order to test the sensitivity of the life cycle cost analyses to initial cost variations, life cycle cost analyses were completed for three initial costs for each RUMAC type evaluated in Table 4.1. The highest initial cost (higher CRM price and no incentive) and the lowest initial cost (lower CRM price and maximum incentive for disposal savings) were used, as well as the average of the two. These figures were used to

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[1] Royal Bank of Canada, Currency & Credit Market Outlook, International exchange rate and credit market forecasts, Royal Bank of Canada Economics Department - Treasury & Financial Markets, June 1993.

TABLE 4.2 LIFE CYCLE COST ANALYSIS SUMMARY FOR CONVENTIONAL AND RUMAC MIXES - 30 YEAR LIFE

MIX TYPE	LIFE CYCLE COST, dollars/lane-km			
	REPLACEMENT FREQUENCY			
SURFACE COURSE	5 YEARS	10 YEARS	15 YEARS	20 YEARS
HL 3 CONVENTIONAL			49753	
HL 3 (1½%) RUMAC CRM @ $ 300/t + 30 Del. + No incentive [42.50/t]	128703	74234	54632	41919
CRM @ $ 200/t + 20 Del. + maximum incentive [37.60/t]	121340	69971	51392	39438
Mean [40.05/t]	125024	72104	53013	40679
HL 3 (2%) RUMAC CRM @ $ 300/t + $ 30. Del. + no incentive [44.95/t]	132382	76364	56251	NA
CRM @ $ 200/t + $ 20. Del. + maximum incentive [38.42/t]	122572	70684	51934	NA
Mean [41.69/t]	127484	73528	54096	NA
BINDER COURSE	20 YEARS	25 YEARS	30 YEARS	
HL 8 CONVENTIONAL	26079	23756	21778	
HL 8 (2%) RUMAC CRM @ $ 300/t + $ 30. Del. + no incentive [34.92/t]	31266	28674	26467	
CRM @ $ 200/t + $ 20. Del. + maximum incentive [29.92/t]	28178	25742	23672	
Mean [32.42/t]	29720	27208	25077	
HL 8 (3%) RUMAC CRM @ 300/t + $ 30. Del. + no incentive [40.92/t]	34976	32192	29822	
CRM @ $ 200/t + $ 20. Del. + maximum incentive [31.05/t]	28872	26405	24304	
Mean [35.99/t]	31928	29302	27066	

determine the cost per lane-km of pavement for each HMA and RUMAC mix, assuming a thickness of 40 mm for the surface course life cycle cost evaluations and 50 mm for the binder course comparisons.

The life cycle costing was conducted for a 30 year service life, with various performance assumptions and maintenance scenarios (both optimistic and pessimistic). For instance, each HL 3 RUMAC surfacing was life cycle costed for replacement (milled off and replaced with the same mix type) at intervals of 5, 10, 15 and 20 years respectively. Monitoring of the generic dry process RUMAC projects completed to date suggests that the mixes containing 1.5 percent CRM should last between 10 and 15 years, while 5 to 10 years is expected for some mixes containing 2 percent or more CRM when ravelling will necessitate provision of an overlay.

The life cycle costing of the conventional HMA and RUMAC surface course mixes also assumed that routine maintenance activities such as crack sealing, pothole filling, etc. would be provided on a regular scheduled basis. For example, crack sealing of an asphalt pavement would typically be completed within the first two years of construction or major rehabilitation (overlay) and again five years thereafter (properly applied, hot poured rubberized crack sealants last between 5 and 7 years). The same schedules and level of maintenance were assumed for both conventional and RUMAC mix types, with additional analyses completed assuming that the RUMAC mix would require half the maintenance.

Similar life cycle cost analyses were completed for the conventional HMA and RUMAC binder course mix types. As these mixes would be covered with a surface course layer, the life cycle costing does not include any routine maintenance operations, and only reflects the schedule for replacement (milling and replacement with the same mix type). Replacement schedules of 20, 25 and 30 years were costed for both conventional HMA and RUMAC binder course mixes.

The life cycle cost analyses indicate that the lowest life cycle costs are obtained for the conventional HL 3 surface course and HL 8 binder course mixes. Even when a relatively low CRM price and maximum incentive is assigned to the RUMAC mixes, the life cycle costs of the RUMAC alternatives are still more than the conventional mixes. Even if the RUMAC mixes require half the level of maintenance, they are still more costly. Only when the RUMAC surface course design life is extended to 20 years, with low CRM pricing and maximum incentive, and compared to a 15 year design life for conventional HMA surface course is the life cycle cost less than conventional. However, this is considered to represent a very optimistic scenario from the Ontario generic dry process RUMAC performance data to date.

4.4 LIFE CYCLE COST ANALYSIS FOR AR

The life cycle cost analysis for wet process continuous blending AR was somewhat simplified compared to the detailed RUMAC analysis, in order to use US data in the Ontario context. Several assumptions were made for the AR analysis: surface course (HL 3) use will be typical; Rouse technical and costing data (Subsection 2.7) are appropriate (about 20 percent increase in hot-mix materials cost, or $ 5.00/tonne of hot mix, attributable to AR incorporation, which also appears reasonable for Ontario) (Rouse, 1993a.); and no external incentives (tire buffings can be readily used in lieu of CRM). The life cycle cost analysis was completed for several performance assumptions: HL 3 surface course service life is typically 15 years; AR HL 3 surface course service lives of 15 years and 20 years (Metro Toronto Transportation apparently experiencing longer service life, for instance); same maintenance required for HL 3 and AR HL 3; and one half the maintenance required for AR HL 3. The initial cost of the two mixes is taken as $ 34./tonne for conventional HL 3 and $ 39./tonne for AR HL 3.

Comparative life cycle cost analyses for AR HL 3 and conventional HL 3 are presented in Table 4.3 for the various performance assumptions. If the incorporation of wet process continuous blending AR in HL 3 does decrease the maintenance cost and/or extend the service life, as anticipated, then there is certainly a potential for considerable savings on a life cycle cost basis. This is the position taken by US proponents of AR use, who also emphasize the technical advantages of AR such as durability/enhancement in open-graded hot mix, SAM, SAMI, etc. applications (ARPG, 1989; International Surfacing, 1992; Rouse 1993a.,b.).

TABLE 4.3 ASPHALT RUBBER (AR) LIFE CYCLE COST ANALYSIS SUMMARY - 30 YEAR LIFE

MIX TYPE	LIFE CYCLE COST, dollars/lane-km	
	REPLACEMENT FREQUENCY	
	15 YEARS	20 YEARS
HL 3 CONVENTIONAL Regular Maintenance	49753	
AR HL 3, Same Maintenance As HL 3	53167	40887
AR HL 3, Requiring half the maintenance as HL 3	47241	34509

5. REVIEW OF ENVIRONMENTAL LITERATURE

The review of environmental impacts for rubber modified asphalt (RUMAC) projects relative to conventional asphalt production, includes consideration of air, water, waste and occupational health and safety concerns. A comprehensive review of the technical literature was completed to summarize environmental impact information for recent projects similar to the MOEE/MTO demonstration projects, or more advanced modified rubber asphalt development or production programs in other jurisdictions having climates, environmental and highway design standards similar to Ontario.

The environmental literature review consisted of: computerized searches of the environmental information databases (including Environmental Abstracts, Enviroline and National Technical Information System (NTIS) accessible through DIALOG Information Service); review of published studies, reviews and articles in the JEGEL and ORTECH environmental and construction materials libraries, and documents obtained through personal contacts in Canada, United States and internationally.

5.1 AIR EMISSIONS

A joint report by the United States Environmental Protection Agency (EPA) and the Federal Highway Administration (FHWA), United States Department of Transportation provides a relatively comprehensive summary of comparative air emission studies completed to date for conventional hot-mix asphalt and rubber modified asphalt production in North America, and includes two of the MOEE/MTO demonstration projects (MTO Thamesville - Phase I and Haldimand-Norfolk Trial #1) that are also reviewed in Chapter 6 of this report (FHWA/EPA, 1993). EPA, in an attempt to characterize the relative human health and environmental risks associated with rubber modified asphalt versus conventional hot-mix asphalt, had previously determined that the existing data were not adequate for this purpose. As a result, FHWA/EPA evaluated a number of modified asphalt demonstration projects throughout North America. The projects were reviewed in order to determine if a significant difference in hazardous emissions corresponding to relative exposure risks existed between rubber modified asphalt and conventional asphalt, and to conduct a risk assessment of hot-mix asphalt production using recycled materials including crumb rubber.

Three approaches to risk assessment of complex materials such as hot-mix asphalt are recommended by EPA, and may be selected on the basis of availability and quality of data:

1. Using data for the mixture of concern - these data are usually not available or difficult to obtain due to the variable nature of the mixture of concern;
2. Using data for similar mixtures - data for similar mixtures can have a high degree of uncertainty due to the difficulties in matching the specific mixture of concern.
3. Using data for the individual components of the mixture - the risk associated with each component is combined to determine a cumulative risk. The composition of the mixture of concern and data on the individual components are required, along with some understanding of the interactions between the components. The risk may be underestimated or overestimated by the uncertainty caused by the effects of interactions between the components.

The following major issues were identified in the FHWA/EPA report to be addressed in order to assess the relative risks of using RUMAC versus conventional HMA asphalt:

- Are the chemical compositions of conventional and rubber modified asphalt mixtures, and emissions from production, application, and recycling of these mixtures, adequately characterized to support hazard identification?
- Is the environmental monitoring data adequate to support assessments of exposure to humans or other organisms in the environment?
- Is the information on the environmental fate and toxicity of the major hazardous constituents of asphalt pavements and modifying agents adequate to support exposure models?
- Is there adequate information on dose-response relationships for components of conventional and modified asphalt paving mixtures, and/or for the mixtures of concern or similar mixtures?
- Are the toxicological interactions that occur between the chemical constituents of modified asphalt pavements adequately characterized?

The FHWA/EPA report states that hot-mix asphalt production is by nature a highly variable process, dependent on parameters such as fueling rate of the drier, mix temperature, asphalt throughput (production) rate and asphalt binder content, which are in themselves subject to variation. Due to this variable nature, extensive sampling is required to determine emission rates with the degree of precision necessary to differentiate between emissions from conventional and modified asphalt pavements. It was found that the previous studies lacked extensive sampling and would not support statistical analysis. It was determined that only very broad patterns of the data from these studies could be identified due to the inability to apply proper statistical analysis. Mean values of the data were used for comparisons and offered only rough indications of trends. Due to the unreliability of the data, emission rate differences between conventional and modified asphalt pavements of less than one order of magnitude (10-fold increase or 90 percent decrease) were arbitrarily not generally considered to be meaningful by FHWA/EPA.

The FHWA/EPA report observations indicate that the inter-study range of emission rates is similar to, or exceeds, the intra-study ranges for most chemical compounds between conventional and rubber modified paving mixtures. The inter-study ranges exceed a factor of 10 for many compounds and a factor of 1000 for others. The report suggests that potential sources of variation include the type of plant, type of burner fuel, emission control system, source of asphalt cement, mix specifications, mix temperature, the process by which rubber is added to the mix and CRM particulate size and gradation. For instance, it was noted that the magnitude of the difference in polynuclear aromatic hydrocarbon (PAH) emission levels associated with the addition of CRM to the mix may be insignificant compared to differences resulting from other variables such as the type of mixing plant. This leads to the conclusion that the impact of CRM on emissions may be relatively small compared to the impacts of other variables.

A consistent finding of this report pertains to the presence of 4-methyl-2-pentanone (MIBK) only during mixing of rubber modified asphalt. The MIBK emissions comprised a significant portion of the total volatile emissions ranging from 5 to 32 percent of total volatile emissions. The presence of the MIBK is considered to result from thermal degradation of isoprene. Higher rates of emission of MIBK were also observed during mixing at higher temperatures. MIBK is a skin and mucous membrane irritant and moderately toxic by inhalation. MIBK is not considered a carcinogen.

The FHWA/EPA report conclusions were based on the following simplistic assumptions:

- the processing methods used for the MTO Thamesville - Phase I, Haldimand-Norfolk Trial #1, Parmer County (Texas), and San Antonio (Texas) studies are representative of the methods used in other plants;
- emission rates for the compounds monitored in these studies provide good indices of exposure levels in the immediate vicinity of the plant; and
- the exposure levels determined from these studies represent the major determinants of the upper bound of risk that would apply to populations of all species at all locations.

For most compounds, the magnitude of the differences in emissions between the modified and the conventional processes within a particular project were relatively small compared to differences between projects. This suggests that, for most compounds, the difference in emission rates resulting from the addition of CRM to the mix are smaller (or at least no larger than) the difference attributed to other factors. If the above three assumptions hold, then it can be concluded that the risks associated with release of these compounds from asphalt paving mixtures modified with CRM is no greater than the risks associated with conventional asphalt paving mixtures. This conclusion may not apply to MIBK, which was consistently observed to be emitted from modified asphalt paving mixtures, but not conventional asphalt paving mixtures.

A personal communication from the State of New Jersey to the project team outlined its current activities in the area of CRM research (Baker, 1993). In 1991, an asphalt-rubber wet process project was completed consisting of a 50 mm (2 inch) thick surface course overlay containing 10 percent fine ground tire rubber which was added to the heated asphalt cement before being mixed with the aggregate in the pugmill. Air quality surveys were conducted for odours and visual emissions during hot-mix production. No odours or significant visual emissions were noted at the plant during hot-mix asphalt production.

Another wet process project involving asphalt cement containing 15 percent crumb rubber was monitored by stack tests for particulates, carbon monoxide, total hydrocarbons, oxygen, stack opacity and odours. All test results were reported to be within New Jersey Department of Environmental Protection and Energy (NJDEPE) standards (Baker, 1993).

In addition, the State of New Jersey also conducted several dry process studies. Stack emission tests were conducted for a RUMAC mix containing 1 percent

CRM for particulates, carbon monoxide and hydrocarbons. Air emissions were reported to be within the NJDEPE standards (Baker, 1993).

5.2 OCCUPATIONAL HEALTH

The use of scrap tires in asphalt paving has stimulated concerns about potential occupational exposures to chemical compounds in the fumes generated during asphalt concrete production. A number of studies have been completed that have attempted to investigate occupational health and safety exposure levels for workers at hot-mix asphalt plant and paving sites where conventional and rubber modified asphalt is involved.

An extensive study conducted for the Florida Department of Transportation investigated potential occupational exposures over a three-day period when RUMAC was placed compared with a three-day period of conventional hot-mix asphalt paving (Radian, 1993). Both personal breathing zone and stationary area sampling were conducted. All levels monitored at the personal breathing zone during RUMAC and conventional hot-mix asphalt paving were below permissible exposure limits. Many of the target compounds were not detected, or only infrequently and at low concentrations. This study reports that total particulate levels of area samples were higher for the RUMAC than for the conventional hot-mix asphalt. However, personal breathing zone particulate levels were not significantly different between conventional and RUMAC paving. The PAH compound phenanthrene was also found to be at higher concentrations during RUMAC placement. However, due to the small sample size involved in the phenanthrene monitoring, and the fact that the temperature of the RUMAC material was 10 to 20°C (50 to 70°F) above the normal conventional HMA temperature casts serious doubt as to whether this finding would apply to other paving operations.

The National Asphalt Paving Association (NAPA) has also released a study conducted to investigate occupational exposure to asphalt rubber fumes (NAPA, 1993). In this study, asphalt-rubber hot mix was processed with sampling conducted during a two-day paving period in California. The asphalt cement produced contained 20 percent rubber and the asphalt cement content of the hot-mix asphalt was 10 percent. The asphalt-rubber hot mix was applied to the road at temperatures of 103°C to 175°C (270°F to 350°F). Both personal breathing zone and area samples were taken. Particulate levels were in the range expected for conventional paving operations. Levels for the specific PAH compounds anthracene, fluoranthene, fluorene, phenanthrene and pyrene were higher than levels anticipated during conventional paving operations. However, the small number of samples again prevents meaningful comparisons between conventional hot-mix asphalt and rubber modified asphalt from being developed.

In a study completed over a three-year period by the Asphalt Rubber Producers Group (Rink et al, 1991), sampling was conducted during the mixing or laying of asphalt-rubber hot-mix asphalt, spraying of asphalt-rubber and aggregate membrane, and conventional paving operations. The report concludes that the exposure levels during the asphalt-rubber operations did not differ from those of conventional asphalt operations. Worker exposure to benzene and marker PAH compounds were either below or approaching the detection limit in all cases. Coal tar pitch soluble volatiles (benzene-solubles) exposure levels for the asphalt-rubber operations ranged from below the detection limit to a high of 7.8 mg/m^3. Comparative data from conventional hot-mix asphalt paving operations ranged from 0.15 to 5.6 mg/m^3.

The FHWA/EPA report previously mentioned in Section 5.1 also reviewed the NAPA and ARPG worker exposure studies and presents additional data on worker exposures to total particulates. It concludes that there may be relationships between rubber modified asphalt pavement operations and exposure to particulates and PAH, but the results of the studies do not provide any real evidence for the existence of such relationships. The data for conventional asphalt paving operations show ranges of values without averages. Upper limits of the ranges, while in some instances exceeding permissible levels, do not represent average conditions and should not be considered as typical.

5.3 WASTE MANAGEMENT

The waste management issues of concern must consider all waste materials resulting during the production and placement of asphalt paving materials. Waste materials generated at the paving site typically include out-of-specification or excess hot-mix asphalt material, with waste water and sludge from wet scrubber systems, or baghouse fines from dry dust collection systems, the principal wastes generated at the asphalt plant site.

Waste water from wet scrubber systems may require collection for disposal or sewering if the level of contaminants exceeds the regulatory limits for on-site disposal (Ontario Provincial Water Quality Guidelines for instance). Similarly, solid waste materials such as baghouse fines might require leachate testing (in accordance with Ontario Regulation 347 requirements for instance) for waste classification prior to being accepted at approved disposal sites.

The literature review did not indicate substantial information pertaining to waste management issues for conventional and rubber modified asphalt material. There were, however, several reports that presented conclusions developed from leachability tests of both conventional and rubber modified asphalt products.

An Asphalt Institute study (AI, 1991) reports on work completed by Heritage Research Group where TCLP (Toxic Characteristic Leachability Procedure) leachate from fresh hot-mix asphalt was used to test for the presence of the forty EPA contaminants and the high-molecular weight PAHs routinely required by EPA. The hot-mix asphalt used in this study consisted of AC-20 asphalt cement with slag, stone and sand meeting Indiana DOT specifications for asphalt surface mixtures.

Of the forty contaminants identified by the EPA as hazardous, chromium was the only compound above detection limits, and was concluded to have leached from the slag aggregate. The only detectable PAH was naphthalene, which was well below the established EPA guidelines. This study concluded that hot-mix asphalt does not leach any hazardous constituents.

An FHWA study by Purdue University reports the findings of a Minnesota Pollution Control Agency study[1]. (FHWA, 1991) on the use of tire rubber as fill as follows:

- Metals are leached from tire materials in the highest concentrations under acid conditions, with the constituents of concern being barium, cadmium, chromium, lead, selenium and zinc
- PAH compounds and petroleum hydrocarbons are leached from tire materials in the highest concentrations under basic conditions
- Asphalt may leach higher concentrations of contaminants of concern than tire materials under some conditions

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1. MPCA, Waste Tires in Sub-grade Road Beds - A Report on the Environmental Study of the Use of Shredded Waste Tires for Roadway Subgrade Support, Minnesota Pollution Control Agency, St. Paul, MN, 1990.

- Drinking water Recommended Allowance Limits (RALs) may be exceeded under 'worst-case' conditions for certain parameters
- Co-disposal limits and EPA Toxicity limits are generally not exceeded for the parameters of concern
- Potential environmental impacts from the use of waste tires can be minimized by placement of tire materials only in the unsaturated zone of the subgrade.

An article from Rubber & Plastics News describes the major pollutants from bottom ash from tire fires as zinc, copper, iron, lead, and mercury (Moore, 1991). Since these compounds originate from the tires, they should be included for analysis in any leachate testing.

It has not been possible to determine significant differences with regards to waste management issues between conventional asphalt and rubber modified asphalt with the limited information available. Issues that have not been resolved include determining if there are leachable contaminants from the solid waste of RUMAC and AR processes and if these leachable contaminants render the waste unacceptable for landfill disposal. Potential contaminants listed in the literature include naphthalene, barium, cadmium, chromium, lead, selenium, zinc, copper and mercury.

If any RUMAC, RRUMAC, RUMCIP or AR pavement is eventually unsuitable for recycling due to technical factors such as quality or leachate concerns, or supply factors such as too much reclaimed asphalt pavement (RAP) being available in the area, there could be significant disposal costs involved. The quantities of RAP for disposal (waste management) would, of course, be much greater than the amount of CRM incorporated. Recyclability, from an asphalt technology viewpoint, does not currently appear to be a problem from the available technical information. Also, if not recyclable into asphalt mixes (binder course hot-mix asphalt for instance), the RAP could still be used as granular material, which is already Ontario practice for some conventional RAP. There do not appear to be any leachate problems associated with conventional HMA or conventional RAP (Thompson and Haas, 1992). For these reasons, it is considered unlikely that there will be any old asphalt long term waste management problems due to CRM use. However, this recyclability issue for rubber modified asphalt should be kept in mind when considering the various recommendations given in Section 8.

5.4 GROUNDWATER AND SURFACE WATER QUALITY

There are three sources of contamination of ground and surface water resulting from the production and application of conventional and rubber modified asphalt:

1. On-site disposal of wastewater from wet scrubber systems;
2. Air emissions from the production and application processes; and
3. Leachate from stockpiled or in-place asphalt concrete.

Many asphalt plants may not have access to sanitary sewer systems and, therefore, there is the concern for potential contamination of surface and groundwater from on-site disposal if the wastewater or leachate exceeds established guidelines. No literature was found that examined the level of contamination of wastewater from either conventional asphalt or rubber modified asphalt production.

Air emissions that result from the production and placement processes can be a potential threat to surface and ground water. These emissions may be deposited into surface waters or onto soil. Their mobility within the soil will be dependent on their solubility in water. Ground water may be impacted as the contaminants travel through the soil. The FHWA/EPA report referred to in Section 5.1 found that MIBK was consistently present only during mixing of rubber modified asphalt. It was stated in this report that this compound has relatively high water solubility and a low soil adsorption coefficient, suggesting that it would be highly mobile in soil, making it a potential groundwater contaminant.

Leachate from in-place asphalt concrete pavement could potentially affect ground and surface waters. As the asphalt concrete ages and cracks to expose fresh surfaces, the concentration of compounds in the leachate could increase. Results of leachability testing on asphalt, as discussed in the previous section, are somewhat limited to date but do not indicate any problems with asphalt concrete leachability. The FHWA/EPA report attempts to put this issue into perspective by stating that the mobility of toxic components of CRM from in situ rubber modified pavement should to be measured against the mobility of toxic components from residual rubber left on the road surface from normal tire wear.

A claimed beneficial characteristic of rubber modified pavement that could directly affect ground and surface water quality may be its elasticity. Rubber makes the road surface deform elastically under traffic, which helps to break up ice deposits on the road (SEPA, 1991). This characteristic could contribute to an overall reduction in the use of road deicing salt.

6. ENVIRONMENTAL REVIEW OF ONTARIO DEMONSTRATION PROJECTS

6.1 BACKGROUND

A number of demonstration projects were funded by MOEE and MTO between 1990 and 1992 to evaluate the technical feasibility of using crumb rubber in asphalt pavements. The objective of these demonstration projects was to determine the technical and environmental differences and similarities between RUMAC and conventional HMA materials. The projects covered production and application processes.

From an environmental impacts point-of-view, six of the projects focused on health and safety impacts, and specifically chemical emissions to the air and worker exposure to emissions. Only two projects (MTO Thamesville - Phase I and Phase II) focused on the associated waste management issues of asphalt production and the potential contamination of ground and surface waters.

The aim of the study described in this section is to draw conclusions and propose recommendations on the use of crumb rubber in asphalt, based on the results of the environmental monitoring that was performed at these sites. The main focus of the monitoring was on the asphalt plant stack emissions since it comprises the most comprehensive data. Any attempt to make comparisons between the results of the rubber modified asphalt processes and the conventional asphalt processes is complicated by the differing conditions that existed at the various plants, as they will directly affect the results. Differing conditions such as plant type, hot-mix asphalt composition and constituents, pollution control equipment, operating temperatures and weather will all contribute to variations in stack emissions. In addition to differences in process conditions, there were also differences in testing as a result of different groups performing the sampling and analysis.

The six projects where environmental monitoring was completed consisted of four different hot-mix asphalt plants. Three of the plants are batch-type mixers, while the fourth is a continuous drum mixing plant. Asphalt concrete mix designs for each material contained varying sources and quantities of aggregates, asphalt cement, processed CRM and in one case, reclaimed asphalt pavement (RAP). Both fabric filter baghouses and wet scrubbers were involved for pollution control, with one plant exhausting fumes from the mixing unit directly (drier fumes only collected by a baghouse).

Operating temperatures were not consistent for duplicate tests and were normally higher for rubber modified processes. Projects were conducted in spring, summer and fall and were thus subjected to seasonal variations.

6.2 AIR EMISSIONS

The air emission studies carried out during the six demonstration projects focused primarily on the following classes of contaminants:

Inert Particulates
Trace Metals
Acid Gases

Combustion Gases

Volatile Organic Compounds (VOCs)

Polynuclear Aromatic Hydrocarbons (PAHs)
Dioxins and Furans
Chlorobiphenyls
Chlorophenols
Chlorobenzenes

Each of these categories included a number of individual chemical species (ranging from seven for acid gases to thirty-eight for trace metals). For clarity of presentation, the total emissions for each category have been used as the primary means of comparison between conventional and RUMAC mixes in this analysis.

In all cases, the sampling portion of the demonstration projects was performed according to the requirements outlined in the MOEE Source Testing Code (MOEE Report No. ARB-66-80) using accepted reference methodologies. Analytical methods were based on published referenced methods from the EPA, Environment Canada and the MOEE.

Inert particulates, trace metals and acid gases were sampled using an MOEE Method 5 sampling train with modified impingers as per California Air Resources Branch (CARB) Method 436 (Modified Method 5).

All combustion gases were monitored using the continuous emission monitoring instrumentation in the MOEE's mobile laboratory, referred to as the Mobile Air Pollution System (MAPS) vehicle. The instrumental sampling methodologies were based on methods from the EPA Code of Federal Regulations, Title 40 - Protection of Environment, Part 60.

Volatile organic compounds were sampled using a Volatile Organic Sampling Train (VOST) according to U.S. EPA Method 30.

Polynuclear aromatic hydrocarbons (PAH), dioxins, furans, chlorobiphenyls, chlorophenols and chlorobenzenes were sampled using a Modified MOEE Method 5 sampling train. PAH, dioxins and furans were analyzed according to EPA Method 23.

6.2.1 Overview

The emission data for all contaminants have been expressed both as concentrations at the point of emission (mg/m^3) and as emission factors based on the quantity of hot-mix asphalt produced during the testing program (mg/Mg). The concentration data are in the form of milligrams of contaminant released per cubic metre of process gas in the emission stack. The emission factor data are in the form of milligrams of contaminant released per tonne of hot-mix asphalt produced. For the purposes of comparison, only the emission factors have been used as these data are normalized according to individual plant production rates.

The Study design and subsequent data generated from the six projects were not of the required quality for a rigorous statistical analysis. The number of tests performed for conventional HMA and RUMAC ranged from one to four from each project, and the process conditions at each project were sufficiently different to prevent a direct combination of the emission data across all projects. For example, in the Haldimand-Norfolk Trial #1 project, one test was performed for conventional HL 3 asphalt, two tests were performed for HL 3 RUMAC containing 2 percent CRM and one test was performed for HL 8 RUMAC containing 3 percent CRM. For the MTO Thamesville - Phase II project, four tests were performed for conventional RHM (70/30) hot-mix asphalt containing 30 percent conventional RAP, three tests were performed for RHM (70/30) hot-mix asphalt containing 30 percent RAP and 3 percent CRM, and three tests were performed for HL 4 RUMAC containing 3 percent CRM.

Consequently, the mean value of each series of tests for a given project has been used as the primary method of comparison, similar to the EPA study method previously described. This is summarized for each contaminant category for all projects in Table 6.2-1. Table 6.2-1 directly compares the air emission results for conventional HMA versus RUMAC mixes. Where applicable, the standard deviation of the mean is also included for each value.

There are no overall trends readily apparent from the demonstration project data summaries. The mean values for a given contaminant category do not display a consistent increase or decrease between conventional HMA and RUMAC mixes used for the six projects monitored. This can be clearly seen in Table 6.2-1. The degree of variation between conventional HMA and RUMAC for total PAHs ranged from essentially no difference to a two orders of magnitude increase for the Grey County Road 12 project. In several cases (specifically, total metal emission factors for MTO Thamesville - Phase II and total dioxin and furan emission factors for MTO Thamesville - Phase I), there was a two order of magnitude decrease in emission factors between conventional HMA and RUMAC mixes.

Table 6.2-1 is also a good indicator of the variation between demonstration projects for the same contaminant. For total particulates, the conventional asphalt emission factors range from 2,567 mg/Mg to 540,800 mg/Mg. For VOCs, the RUMAC emission factors range from 197 mg/Mg to 4,157 mg/Mg.

The chemical class emission rates for these Ontario studies for both conventional HMA and RUMAC overlap and exceed the differences between conventional HMA and RUMAC emission rates determined within each study. For example, the ratio of particulate emission factor means for the project (Table 6.2-1) ranged from 0.4 to 2.0 while the actual particulate emission factors for all projects ranged from 2,567 mg/Mg to 540,800 mg/Mg for conventional HMA and from 1,940 mg/Mg to 574,600 mg/Mg for RUMAC.

Arbitrarily setting a difference of at least one order of magnitude as being the minimum requirement for a significant difference between products, the pollutant categories that displayed no significant differences for all projects were total chlorobiphenyls, total combustion gases and total acid gases. All other pollutant categories had at least one demonstration project with an order of magnitude or greater difference between conventional HMA and RUMAC emission factors.

TABLE 6.2-1 COMPARISON OF AIR EMISSIONS FROM CONVENTIONAL ASPHALT AND RUBBER MODIFIED ASPHALT PRODUCTION

CONTAMINANT CATEGORY	PROJECT ID*	CONVENTIONAL ASPHALT				RUBBER ASPHALT				Ratio of Emission Factor Means (Rubber/ Conven.)
		Fluegas Concentration		Emission Factor		Fluegas Concentration		Emission Factor		
		Mean mg/m3	Standard Deviation of Mean mg/m3	Mean mg/Mg	Standard Deviation of Mean mg/Mg	Mean mg/m3	Standard Deviation of Mean mg/m3	Mean mg/Mg	Standard Deviation of Mean mg/Mg	
TOTAL PARTICULATES	1	236.0	27.54	33,380	4,165	451.4	228.1	67,130	33,000	2.0
	2	3,412		540,800		4,237	321.8	574,600	118,000	1.1
	3(A,C)	928.8	293.5	172,500	59,510	123.0	9.794	24,040	1,269	0.1
	3(A,B)	928.8	293.5	172,500	59,510	1,098	151.9	192,700	29,730	1.1
	4	9,929	87.62	480,200	362,000	13,080	2,998	169,400	31,240	0.4
	5					2,290	194.7	302,700	9,969	
	6	8.072	1.847	2,567	712.0	5.663	2.080	1,944	726.6	0.8
TOTAL METALS	1	44.65	10.39	6,070	1,285	29.57	4.450	4,427	628.9	0.7
	2	1,200		190,200		1,243	44.03	165,800	18,850	0.9
	3(A,C)	179.0	89.73	32,400	16,010	8.164	0.8484	1,606	178.1	0.05
	3(A,B)	179.0	89.73	32,400	16,010	54.36	10.51	9,464	1,886	0.3
	4	2,750	125.5	32,880	1,167	3,982	601.9	51,910	5,953	1.6
	5					822.7	57.84	108,300	1,517	
	6	22.10	2.067	6,654	252.2	10.79	0.9853	3,642	350.8	0.5
TOTAL DIOXINS AND FURANS	1	2.041E-05	8.379E-06	2.817E-03	1.155E-03	8.433E-07	5.313E-07	1.251E-04	7.785E-05	0.04
	2	6.000E-07		9.403E-05		1.713E-06	4.392E-07	2.196E-04	5.021E-05	2.3
	3(A,C)	2.416E-06	7.857E-07	4.486E-04	1.457E-04	4.707E-07	2.382E-07	8.678E-05	4.347E-05	0.2
	3(A,B)	2.416E-06	7.857E-07	4.486E-04	1.457E-04	7.204E-06	2.388E-06	1.296E-03	4.578E-04	2.9
	4	4.387E-07	2.090E-08	4.278E-06	2.028E-07	1.011E-06	1.021E-07	1.102E-05	1.091E-06	2.6
	5					5.860E-06	6.162E-07	7.634E-04	6.890E-05	
	6	2.332E-07	9.146E-09	7.182E-05	3.342E-06	2.243E-07	1.967E-08	7.578E-05	6.614E-06	1.1
TOTAL CHLOROBIPHENYLS	1	4.387E-04	1.038E-04	5.976E-02	1.384E-02	3.033E-04	4.405E-05	4.548E-02	6.345E-03	0.8
	2	1.186E-04		1.846E-02		1.897E-04	5.135E-05	2.654E-02	6.751E-03	1.4
	3(A,C)	0	0	0	0	0	0	0	0	
	3(A,B)	0	0	0	0	0	0	0	0	
	4	1.133E-02	6.904E-05	1.096E-01	1.053E-03	7.407E-03	7.250E-05	8.184E-02	1.435E-03	0.7
	5					1.872E-03	1.017E-03	2.673E-01	1.475E-01	
	6	1.899E-03	6.735E-06	5.848E-01	9.410E-03	1.931E-03	2.430E-06	6.534E-01	3.005E-03	1.1

* See List at end of Table.

TABLE 6.2-1 (Continued)

CONTAMINANT CATEGORY	PROJECT ID*	CONVENTIONAL ASPHALT				RUBBER ASPHALT				Ratio of Emission Factor Means (Rubber/ Conven.)
		Fluegas Concentration		Emission Factor		Fluegas Concentration		Emission Factor		
		Mean mg/m3	Standard Deviation of Mean mg/m3	Mean mg/Mg	Standard Deviation of Mean mg/Mg	Mean mg/m3	Standard Deviation of Mean mg/m3	Mean mg/Mg	Standard Deviation of Mean mg/Mg	
TOTAL CHLOROBENZENES	1	2.443E-05	2.383E-06	3.454E-03	3.737E-04	3.071E-03	3.717E-04	4.640E-01	6.545E-02	134.3
	2	3.760E-05		5.854E-03		4.277E-05	1.410E-05	5.921E-03	2.089E-03	1.0
	3(A,C)	0	0	0	0	0	0	0	0	
	3(A,B)	0	0	0	0	0	0	0	0	
	4	5.050E-03	9.713E-05	4.944E-02	8.653E-04	2.427E-02	2.005E-02	2.434E-01	1.961E-01	4.9
	5					6.460E-04	3.171E-04	8.898E-02	4.634E-02	
	6	8.078E-04	1.862E-05	2.480E-01	5.450E-03	7.955E-04	7.048E-06	2.692E-01	2.832E-03	1.1
TOTAL CHLOROPHENOLS	1	1.023E-04	2.721E-05	1.423E-02	3.724E-03	2.139E-03	1.758E-04	3.221E-01	2.606E-02	22.6
	2	0		0		8.250E-05	3.563E-05	1.064E-02	4.392E-03	
	3(A,C)	4.806E-06	4.806E-06	9.075E-04	9.075E-04	2.828E-04	1.737E-05	5.332E-02	2.374E-03	58.8
	3(A,B)	4.806E-06	4.806E-06	9.075E-04	9.075E-04	1.123E-03	1.523E-04	1.982E-01	3.208E-02	218.4
	4	4.000E-04	1.291E-05	3.762E-03	3.351E-05	4.600E-04	1.000E-05	5.114E-03	1.146E-04	1.4
	5					3.933E-05	3.933E-05	5.650E-03	5.650E-03	
	6	4.396E-04	3.293E-06	1.352E-01	1.812E-03	4.416E-04	1.494E-07	1.494E-01	4.648E-04	1.1
TOTAL POLYCYCLIC AROMATIC HYDROCARBONS	1	3.963	0.877	538.3	115.9	6.886	0.1555	1,037	30.68	1.9
	2	0.4631		72.03		0.2747	0.03824	36.13	4.617	0.5
	3(A,C)	5.357	0.2084	976.5	37.04	4.964	0.7920	951.1	157.8	1.0
	3(A,B)	5.357	0.2084	976.5	37.04	6.598	0.3729	1,121	36.39	1.1
	4	1.386	0.08047	13.36	0.777	150.9	25.30	1,665	265.9	124.6
	5					0.6441	0.1350	82.60	15.65	
	6	0.4256	0.0160	132.3	8.330	0.2215	0.01583	74.83	4.932	0.6
TOTAL VOLATILE ORGANIC COMPOUNDS	1	16.76	5.084	2,348	723.5	7.652	0.636	1,151	95.54	0.5
	2	1.174		184.4		1.500	0.1239	196.5	15.22	1.1
	3(A,C)	10.50	1.695	1,958	335.5	4.162	0.9051	797.7	169.5	0.4
	3(A,B)	10.50	1.695	1,958	335.5	24.64	6.741	4,157	1,044	2.1
	4	3.704	0.6994	39.37	7.485	32.31	6.606	823.0	170.7	20.9
	5					7.783	0.9722	1,050	72.31	
	6	1.195	0.3395	333.7	87.75	1.377	0.1790	463.3	57.36	1.4

TABLE 6.2-1 (Continued)

CONTAMINANT CATEGORY	PROJECT ID*	CONVENTIONAL ASPHALT				RUBBER ASPHALT				Ratio of Emission Factor Means (Rubber/ Conven.)
		Fluegas Concentration		Emission Factor		Fluegas Concentration		Emission Factor		
		Mean mg/m3	Standard Deviation of Mean mg/m3	Mean mg/Mg	Standard Deviation of Mean mg/Mg	Mean mg/m3	Standard Deviation of Mean mg/m3	Mean mg/Mg	Standard Deviation of Mean mg/Mg	
TOTAL COMBUSTION GASES	1	292,400	15,540	38,560,000	2,326,000	274,100	1,679	41,240,000	791,700	1.1
	2	280,400		44,070,000		279,000	1,788	37,500,000	4,662,000	0.9
	3(A,C)	265,200	6,125	48,960,000	1,508,000	274,300	882.4	53,050,000	1,265,000	1.1
	3(A,B)	265,200	6,125	48,960,000	1,508,000	271,800	6,453	47,390,000	2,643,000	1.0
	4	267,200	1,154	2,885,000	53,370	265,300	878.2	3,061,000	167,500	1.1
	5					271,100	3,131	36,380,000	2,222,000	
	6	248,600	3,859	75,830,000	4,475,000	250,600	1,838	84,630,000	1,018,000	1.1
TOTAL ACID GASES	1	30.52	2.776	4,267	236.6	47.90	1.854	7,221	208.8	1.7
	2	0.6630		105.0		0.4747	0.1188	58.92	7.880	0.6
	3(A,C)	60.47	11.79	11,330	1,973	25.83	1.761	4,994	336.9	0.4
	3(A,B)	60.47	11.79	11,330	1,973	83.95	6.259	14,590	384.0	1.3
	5					0.8521	0.03431	114.1	10.58	
	6	0.692	0.4693	190.8	118.3	0.06670	0.004805	22.45	1.499	0.1

PROJECT ID LEGEND

1. MOE/MTO (Thamesville) Phase 1
2. Regional Municipality of Haldimand/Norfolk #1
3. MOE/MTO (Thamesville) Phase II (A,B,C correspond to Processes A,B,C)
4. Grey County - Road 12
5. Regional Municipality of Haldimand/Norfolk #2
6. Grow-Rich

An examination of the speciated emission data revealed several points of interest. The trace metal emission data for all tests consistently displayed relatively high levels of aluminum, calcium, magnesium, sodium and silicon. These materials are likely residue from the filter media used in the sampling procedure. High levels of acetone and other common laboratory solvents were identified in many of the projects. Again, these are most likely the result of residual contamination during the analytical process.

Naphthalene was consistently found to be one of the most significant PAHs, and benzene, toluene, xylenes and styrene were the most significant VOCs over all tests. Toluene, xylene and styrene are common solvents which are mildly toxic if inhaled in sufficient quantities and can cause eye irritation and systemic effects at high levels. Toluene and xylene are non-carcinogenic while styrene is a suspected carcinogen. Naphthalene can cause eye irritation and confusion. Although not listed as a suspected carcinogen, it is an experimental tumorigen and mutagen (Sax and Lewis, 1988). Benzene, a component of petroleum hydrocarbons, causes severe skin and eye irritation and is a known poison and human carcinogen. Five of the demonstration projects showed releases of 4-methyl-2-pentanone (MIBK) during RUMAC production, which were either not present or orders of magnitude lower in the conventional HMA testing. This tends to support the findings of the FHWA/EPA report.

Overall, due to the wide variability of the Ontario data as indicated by the fact that the means of individual project tests were greater than 2 to 3 standard deviations apart, it is not possible to accurately statistically state whether RUMAC has significantly different air emissions than conventional HMA processes. However, based on the facts that the projects covered a variety of conventional HMA and RUMAC processes, and the plants tested covered old plants to good state-of-the-art plants and the emission results of conventional HMA and RUMAC overlapped, the data would indicate that, except for MIBK, there was no discernable difference between conventional HMA and RUMAC emissions.

6.2.2 MTO Thamesville - Phase I [MTO #1]

The first phase of the sampling program at Thamesville was conducted during October of 1990. The asphalt plant tested was a continuous drum mix plant equipped with a venturi scrubber and cyclonic demister as air emission control devices. All of the air emission sampling was performed from the exhaust of the cyclonic demister.

Four tests were conducted for conventional HL 4 asphalt from October 2 through October 5, and three tests were conducted for HL 4 RUMAC on October 11, 15 and 16.

The only contaminant categories that displayed differences between conventional HMA and RUMAC greater than one order of magnitude were: total dioxins and furans (decreased by one order of magnitude); total chlorobenzenes (increased by two orders of magnitude); and total chlorophenols (increased by one order of magnitude).

The most significant PAHs released were 9,10-dimethylanthracene, fluorene, naphthalene and phenanthrene. The most significant VOCs released were benzene, chloromethane, ethylbenzene, styrene, toluene and xylenes.

Emissions of 4-methyl-2-pentanone (MIBK) were identified only during RUMAC production.

6.2.3 Regional Municipality of Haldimand-Norfolk Trial #1 [HN #1]

The site for this project was the Cayuga Materials and Construction Co. Ltd. batch asphalt plant. One test was performed for conventional HL 3 hot-mix asphalt, two tests were performed for HL 3 RUMAC containing 2 percent CRM and one test was performed for HL 8 RUMAC containing 3 percent CRM. The RUMAC testing was performed from October 26 to October 29, 1990, and the conventional HMA testing was conducted on November 15, 1990.

No contaminant categories displayed any differences between the conventional HMA and RUMAC greater than one order of magnitude.

The most significant PAH released was naphthalene. The most significant VOCs released were benzene, 1,1-dichloroethane and toluene. Emissions of MIBK, 2-hexanone and vinyl acetate were found only during RUMAC production.

6.2.4 MTO Thamesville - Phase II [MTO #2]

The asphalt plant tested was a continuous drum mix plant equipped with a venturi scrubber and cyclonic demister as air emission control devices. All of the air emission sampling was performed from the exhaust of the cyclonic demister. The MTO Thamesville - Phase II project looked at the emissions from three asphalt processes:

Process A consisted of conventional RHM (70/30) containing 30 percent conventional RAP

Process B consisted of RHM (70/30) RUMAC containing 30 percent RAP and 3 percent minus No. 10 mesh CRM

Process C consisted of HL 4 RUMAC containing 3 percent minus No. 10 mesh CRM.

Sampling was performed during October 1991. Four tests were conducted for Process A from October 9 through to October 15, three tests were conducted for Process B from October 16 through to October 18, and three tests were conducted for Process C from October 21 through to October 23.

The only contaminant categories that displayed differences between conventional HMA (Process A) and HL 4 RUMAC (Process C) greater than one order of magnitude were: total particulates (decreased by one order of magnitude); total metals (decreased by one order of magnitude); and total chlorophenols (increased by one order of magnitude). For Process B, there was a two orders of magnitude increase in chlorophenols as compared with Process A.

The most significant PAHs released were fluorene, naphthalene, phenanthrene and tetralin. The most significant VOCs released were benzene, 2-hexanone, methylene chloride, styrene, toluene and xylenes. Emissions of MIBK were found from all three processes, with higher levels from the two RUMAC processes. MIBK is a common solvent that can cause irritation to the skin and mucous membranes. It is mildly toxic by inhalation with an occupational threshold limit of 50 ppm. Toluene and xylene, also common solvents, have occupational threshold limit values of 100 ppm.

6.2.5 Grey County - Road 12 [Grey #1]

The asphalt plant tested in this project was a batch facility with no fugitive emissions control system (fabric filter baghouse for aggregate drier emissions only). All sampling was conducted at the pugmill exhaust which is open to the atmosphere and which was modified for sampling purposes. Three tests for conventional HMA were performed on July 15, 16 and 24, 1992. Four tests for RUMAC were performed on November 14, 1991, and May 13, 14 and 15, 1992.

The only contaminant categories that displayed differences between conventional HMA and RUMAC greater than one order of magnitude were: total PAHs (increased by two orders of magnitude); and total VOCs (increased by one order of magnitude).

It should be noted that the process temperature during the RUMAC trials was higher by 20 to 30 degrees Celsius than during the conventional tests due to production considerations. This was thought to be the cause of the increase in PAHs and VOCs, as the higher temperatures would likely increase the volatilization of many of these compounds from the asphalt mix.

The most significant PAHs released were naphthalene and quinoline. The most significant VOCs were methylene chloride and xylenes. Emissions of MIBK were three orders of magnitude greater from the rubber modified asphalt than from the conventional asphalt.

6.2.6 Regional Municipality of Haldimand-Norfolk Trial #2 [HN #2]

The site for this project was the Cayuga Materials and Construction Co. Ltd. batch asphalt plant. Prior to this study, a fabric filter baghouse was installed at the facility. All sampling was performed at the baghouse exhaust stack. Some sampling of pugmill fugitive emissions was performed, however these data are not considered to be representative.

This project only contained data on RUMAC production. Three tests were performed on HL 3 RUMAC on August 10 through to August 12, 1992.

The most significant PAHs released were acenaphthylene and naphthalene. The most significant VOCs released were benzene, 2-butanone, styrene, toluene and xylenes. An analysis for MIBK was apparently not performed for this project.

6.2.7 Grow-Rich Inc. [Grow-Rich]

The batch facility tested in this study was equipped with a cyclone and baghouse to treat particulate emissions from the aggregate drier. The pugmill vented to the baghouse only.

Three tests during conventional HMA production were performed on October 20, 22 and 28, 1992, and three tests for HL 3 RUMAC with 2 percent CRM were performed from November 3 through to November 5, 1992.

No contaminant categories displayed differences between conventional HMA and RUMAC greater than one order of magnitude.

The most significant PAH released was naphthalene. The most significant VOCs released were benzene, ethylbenzene, toluene and xylenes. The emissions of MIBK were essentially the same for conventional HMA and RUMAC production.

6.3 OCCUPATIONAL HEALTH

The only Ontario demonstration projects where data were available for occupational exposure assessment were the MTO Thamesville - Phase I and the three dry operating processes examined in MTO Thamesville - Phase II. The three processes of Thamesville Phase II were:

> Process A consisted of conventional RHM (70/30) containing 30 percent conventional RAP
>
> Process B consisted of RHM (70/30) RUMAC containing 30 percent RAP and 3 percent minus No. 10 mesh CRM
>
> Process C consisted of HL 4 RUMAC containing 3 percent minus No. 10 mesh CRM.

Worker exposures were sampled at the hot-mix plant and at the paving site. Sampling was conducted for coal tar pitch volatiles, asphalt fume, PAHs, total particulate, metals and volatile organic compounds.

With the exception of one total particulate level at the hot-mix plant, all levels at the MTO Thamesville - Phase I project were low and well below Ontario Ministry of Labour permissible exposure limits. During MTO Thamesville - Phase II production and placement, all levels were also low and well below these exposure limits.

With the exception of a few total particulate samples, all parameters, including total particulate, were either below or approaching the detection limits for all processes. This would indicate that worker exposures to hazardous substances for all processes were similar.

6.4 WASTE MANAGEMENT

The only demonstration projects that dealt with waste management issues were MTO Thamesville - Phase I and MTO Thamesville - Phase II. The results presented in the tables that follow in this section are from MTO Thamesville - Phase II. This project consisted of three test processes referred to as Process A, B and C as previously described.

Wastes generated at this site included wastewater and sludge from the wet scrubber system, and out-of-specification HMA production. The wastewater analysis is discussed in Section 6.5.

Leachate tests conforming to Ontario Regulation 309 (now Ontario Regulation 347) were performed on the following waste samples in order to determine whether they would be accepted for disposal at a municipal landfill:

1. Sludge-from venturi scrubber waste water;
2. Conventional Asphalt;
3. Rubber Modified Asphalt; and
4. Rubber.

Sampling was not extensive and, therefore, does not support statistical analysis. For comparison purposes between the three processes, average analytical values and deviations from the average were calculated from the raw data. The data for the crumb rubber were not considered in this study since the material is not used in the conventional HMA production process.

The sludge from the settling tank is comprised of contaminants extracted from the stack gas by the wet scrubber system. Two samples (one sample per settling tank) were taken per day for each process. Table 6.4-1 presents the average analytical results and corresponding deviation for each process. For the parameters analyzed, the data do not indicate a distinct difference in the level of leachable contaminants from the sludge produced by each of the three mix types.

The asphalt concrete samples were taken at the road site when the asphalt was being placed. One sample was taken per day for each mix type. Table 6.4-2 presents the average analytical results and corresponding deviation for each process. For the parameters analyzed, the data do not indicate a distinct difference in leachable quantities from each of the final asphalt products.

In conclusion, it is not possible to distinguish a difference in leachability of the waste materials between conventional HMA and RUMAC based on the results of this study.

6.5 GROUND AND SURFACE WATER QUALITY

The only demonstration projects that dealt with ground and surface water quality issues were MTO Thamesville - Phase I and MTO Thamesville - Phase II. The results presented in the tables that follow in this section are from MTO Thamesville - Phase II. This project consisted of three test processes referred to as Process A, B and C as previously described.

6.5.1 Leachability of In-Place Asphalt Pavement

The leachability characteristics of the asphalt concrete materials as discussed in the above section did not differ significantly between the conventional HMA and RUMAC mix types. This would indicate that there should be no significant difference in impact to ground and surface water quality from the in-place asphalt pavements constructed using these materials. This statement is made based on the assumption that the leachability characteristics of the products will not increase with increased aging. This assumption may or may not be valid.

TABLE 6.4-1 SETTLING TANK SLUDGE LEACHATE TESTS - THAMESVILLE PHASE II

CONTAMINANT CATEGORY	PROJECT UNITS	PROCESS A Sludge Mean	Standard Deviation	PROCESS B Sludge Mean	Standard Deviation	PROCESS C Sludge Mean	Standard Deviation	PROVINCIAL WATER QUALITY OBJECTIVES
Arsenic	mg/L	<.001		<.001		<.001		0.1
Selenium	mg/L	<.001		<.001		<.001		0.1
Mercury	mg/L	<.00005		2.68E-04	1.65E-04	9.29E-05	3.36E-05	2.00E-04
Silver	mg/L	<.005		<.005		<.005		1.00E-04
Boron	mg/L	2.05E-01	7.66E-03	6.75E-02	3.66E-03	5.14E-02	3.40E-03	UTL
Barium	mg/L	4.31E-01	1.75E-02	4.01E-01	1.65E-02	3.39E-01	1.29E-02	UTL
Cadmium	mg/L	<.005		5.25E-03	2.50E-04	5.29E-03	2.86E-04	2.00E-04
Chromium	mg/L	<.01		<.01		<.01		-
Lead	mg/L	<.05		<.05		<.05		5
Benzo(a)pyrene	ppt	<10		<10		<10		-

UTL - Undefined Tolerance Limit

TABLE 6.4-2 ASPHALT PRODUCT LEACHATE TESTS - THAMESVILLE PHASE II

CONTAMINANT CATEGORY	PROJECT UNITS	PROCESS A Final Product Mean	Standard Deviation	PROCESS B Final Product Mean	Standard Deviation	PROCESS C Final Product Mean	Standard Deviation	PROVINCIAL WATER QUALITY OBJECTIVES
Arsenic	mg/L	<.001		<.001		<.001		0.1
Selenium	mg/L	<.001		<.001		<.001		0.1
Mercury	mg/L	<.00005		<.0005		<.00005		2.00E-04
Silver	mg/L	<.005		<.005		<.005		1.00E-04
Boron	mg/L	0.01		0.017	0.003	0.017	0.003	UTL
Barium	mg/L	0.014	0.004	0.015	0.001	0.014	0	UTL
Cadmium	mg/L	<.005		<.005		<.005		2.00E-04
Chromium	mg/L	<.01		<.01		<.01		-
Lead	mg/L	<.05		<.05		<.05		5
Benzo(a)pyrene	ppt	<10		<10		<10		-

UTL - Undefined Tolerance Limit

6.5.2 Wastewater

Wastewater was generated at the MTO Thamesville site as a result of the use of a venturi scrubber system to control air emissions. Like many other asphalt plants, the Huron Construction asphalt plant did not have access to a sanitary sewer and would likely manage its wastewater on site, unless contaminant levels necessitated further treatment or off-site management in accordance with appropriate environmental approvals.

The wastewater from the scrubber system is collected at the outflow from the cyclonic demister and is pumped to a settling tank. A second settling tank was added in series for MTO Thamesville - Phase II. The wastewater collected from the demister is referred to as 'effluent'. The effluent is considered to be the most contaminated stage of the process water cycle.

After settling, the supernatant is recycled back to the scrubber system. The recycle stream is referred to as the 'influent'. The influent is considered to be the 'cleanest' stage of the process water cycle. A nearby lagoon was used to top up the process water.

Samples were taken at the effluent and influent stages of the process water cycle daily for each process. Samples were also taken from the lagoon to determine if it was impacted as a result of the asphalt production activity. Since the contamination of the lagoon would be cumulative as a result of the activity from each of the processes, the analytical data were not considered usable for the purposes of this study. It would not be possible to determine what extent of the contamination was attributable to each asphalt production process. The influent stage was not used for comparative purposes because the contamination level is expected to be at the lowest point. The influent may be effected by cumulative effects since the process water is being recycled and because the suspect lagoon water is being added periodically.

It was expected that any differences in contamination level of the process water between the conventional HMA and RUMAC production would be most evident at the 'dirtiest' stage, the effluent stage.

Table 6.5-2 shows the average analytical result and the corresponding deviation for the parameters analyzed for the effluent. With few exceptions,

TABLE 6.5-2 WET SCRUBBER WASTE WATER ANALYSIS - THAMESVILLE PHASE II

CONTAMINANT CATEGORY	PROJECT UNITS	PROCESS A Effluent Mean	Standard Deviation	PROCESS B Effluent Mean	Standard Deviation	PROCESS C Effluent Mean	Standard Deviation
pH		6.72E+00	1.06E-01	6.66E+00	9.13E-02	7.09E+00	1.61E-01
Field pH		7.24E+00	2.42E-01	6.78E+00	1.07E-01	7.37E+00	1.76E-01
Biochemical Oxygen Demand	mg/L	7.39E+01	9.03E+00	1.96E+02	1.86E+01	1.74E+02	1.45E+00
Total Suspended Solids	mg/L	4.49E+03	1.02E+03	1.01E+04	1.75E+03	4.13E+04	1.96E+04
Field Dissolved Oxygen	ppm	3.00E+00	1.92E+00	1.50E-01	7.64E-02	1.23E+00	9.40E-01
Total Oil and Grease	mg/L	1.26E+02	9.06E+01	2.36E+02	2.58E+01	6.13E+01	4.67E+00
Mineral Oil and Grease	mg/L	5.60E+01	4.01E+01	8.73E+01	1.00E+01	1.60E+01	4.36E+00
Animal Oil and Grease	mg/L	6.97E+01	5.03E+01	1.48E+02	1.62E+01	4.43E+01	2.85E+00
Fluoride	mg/L	4.25E-01	4.79E-02	8.00E-01	1.34E-10	7.00E-01	5.77E-02
Chloride	mg/L	3.95E+01	2.29E+00	6.59E+01	2.39E+00	9.52E+01	2.21E+00
Sulphate	mg/L	1.01E+03	1.72E+02	1.53E+03	3.48E+01	2.03E+03	8.74E+01
Phenols	mg/L	1.19E+00	2.10E-01	3.47E+00	2.03E-01	2.40E+00	3.33E-01
Cyanide(free)	mg/L	1.40E-02	5.26E-03	2.67E-03	1.20E-03	1.60E-02	1.22E-02
Sulphide	mg/L	9.25E-03	4.57E-03	8.23E-02	1.89E-02	7.03E-02	2.32E-02
Total Kjeldahl Nitrogen	mg/L	4.75E+00	9.46E-01	1.50E+01	1.00E+00	2.17E+01	2.96E+00
Silver	mg/L	5.00E-03	0.00	5.00E-03	0.00	5.00E-03	0.00
Aluminum	mg/L	2.70E+00	1.28E+00	4.39E+00	2.97E-01	4.25E+01	1.22E+01
Arsenic	mg/L	5.00E-02	0.00	6.67E-02	1.67E-02	5.00E-02	8.40E-12
Barium	mg/L	7.88E-02	2.22E-02	1.41E-01	5.21E-03	6.76E-01	1.96E-01
Bismuth	mg/L	1.00E-01	0.00	1.00E-01	1.68E-11	1.00E-01	1.68E-11

TABLE 6.5-2 (Continued)

CONTAMINANT CATEGORY	PROJECT UNITS	PROCESS A Effluent Mean	Standard Deviation	PROCESS B Effluent Mean	Standard Deviation	PROCESS C Effluent Mean	Standard Deviation
Cadmium	mg/L	5.00E-03	0.00	5.00E-03	0.00	6.67E-03	1.67E-03
Cobalt	mg/L	3.88E-02	1.13E-02	5.00E-02	8.40E-12	6.67E-02	1.67E-02
Chromium	mg/L	1.00E-02	0.00	1.00E-02	0.00	1.10E-01	9.50E-02
Copper	mg/L	3.00E-02	7.07E-03	2.50E-02	1.04E-02	2.60E-01	7.23E-02
Iron	mg/L	2.38E+01	4.57E+00	1.75E+01	8.71E+00	1.16E+02	3.19E+01
Lead	mg/L	5.00E-02	0.00	6.67E-02	1.67E-02	2.87E-01	1.01E-01
Manganese	mg/L	2.67E+00	6.29E-01	4.72E+00	1.10E-01	1.05E+01	1.94E+00
Molybdenum	mg/L	2.00E-01	0.00	2.00E-01	3.36E-11	2.00E-01	3.36E-11
Nickel	mg/L	5.00E-02	0.00	5.00E-02	8.40E-12	1.57E-01	2.91E-02
Phosphorus	mg/L	5.25E-01	2.50E-02	5.00E-01	0.00	2.20E+00	2.65E-01
Antimony	mg/L	1.00E-01	0.00	1.00E-01	1.68E-11	2.00E-01	5.77E-02
Selenium	mg/L	1.00E-01	0.00	1.00E-01	1.68E-11	1.00E-01	1.68E-11
Tin	mg/L	2.00E-01	0.00	2.00E-01	3.36E-11	2.00E-01	3.36E-11
Titanium	mg/L	1.63E-01	5.42E-02	2.85E-01	1.04E-02	1.17E+00	2.53E-01
Vanadium	mg/L	1.95E-02	4.91E-03	2.87E-02	1.20E-03	1.09E-01	2.58E-02
Zinc	mg/L	3.75E-02	1.03E-02	8.43E-01	2.20E-01	1.54E+00	3.40E-01
Chlorobenzene	ug/L					2.00E-01	
Benzene	ug/L	4.68E+00	1.84E+00	1.25E+01	2.84E+00	5.77E+00	2.36E+00
Ethylbenzene	ug/L	2.00E-01	5.00E-02	1.47E+00	1.03E+00	2.00E-01	3.36E-11
Styrene	ug/L			4.00E-01			

TABLE 6.5-2 (Continued)

CONTAMINANT CATEGORY	PROJECT UNITS	PROCESS A Effluent Mean	Standard Deviation	PROCESS B Effluent Mean	Standard Deviation	PROCESS C Effluent Mean	Standard Deviation
Toluene	ug/L	1.45E+00	5.24E-01	3.43E+00	6.23E-01	7.33E-01	6.67E-02
O-Xylene	ug/L	3.67E-01	2.89E-02	5.17E-01	1.01E-01	3.33E-01	3.33E-02
M-Xylene + P-Xylene	ug/L	4.00E-01	1.22E-01	7.83E-01	1.30E-01	4.67E-01	3.33E-02
1-Methylnapthalene	ug/L	1.01E+01	2.11E+00	1.41E+01	2.40E-01	7.90E+00	2.36E+00
2-Methylnapthalene	ug/L	1.30E+01	3.06E+00	1.86E+01	1.56E+00	1.10E+01	2.46E+00
Acenapthene	ug/L	3.95E+00	7.42E-01				
Di-n-octyl pthalate	ug/L						
2,4-Dimethylphenol	ug/L	4.75E+01					
4-Nitrophenol	ug/L	2.01E+02	5.46E+01	1.63E+02	2.57E+01	8.88E+01	1.55E+01
m-Cresol & p-Cresol	ug/L	1.46E+02	2.81E+01	6.21E+02	1.21E+01	3.00E+02	1.24E+02
o-Cresol	ug/L	4.14E+01	1.12E+01	1.71E+02	2.33E+00	6.38E+01	3.11E+01
Phenol	ug/L	4.55E+02	8.93E+01	1.88E+03	8.54E+01	9.50E+02	2.65E+02
1,2,4-Trichlorobenzene	ug/L	8.50E-03	1.06E-03	8.00E-03		6.00E-03	
Pentachlorobenzene	ug/L			1.17E-01	3.43E-02	6.00E-03	

metal levels are significantly higher for Process C. This could possibly be due to cumulative effects as mentioned above.

The organic levels are, with few exceptions, consistently higher for Process B. This occurrence may be due to cumulative effects from Process A and B. The decrease in levels in Process C may be a result in loss due to volatilization during the period between Process B and C which was a period of two days.

Due to possible cumulative effects of the contaminants that cannot be reconciled, no conclusions can be made as to the difference between conventional HMA and RUMAC production processes based on results of analysis of the wastewater.

7. ONTARIO PROJECTS IN CONTEXT

STATE-OF-THE-ART COMPARISON

7.1 RUBBER MODIFIED ASPHALT

The relatively short-term pavement performance experience with the Ontario generic dry process RUMAC projects is very similar to that found by the FHWA/EPA study (FHWA/EPA, 1993). For the RUMAC surface course typically incorporating 1.5 percent No. 10 mesh CRM (cryogenic or ambient), and reasonable paving season placement, the short-term pavement performance is similar to control sections. However, for the RUMAC surface course typically incorporating 2.0 percent No. 4 mesh CRM, and late paving season placement, the short-term pavement performance is very poor to poor compared to control sections. Similar to the FHWA/EPA study finding, there were no problems associated with RUMAC recycling for the one project involved (RRUMAC, MTO #2). In common with the FHWA/EPA study, long-term pavement performance for RUMAC is not available and must be developed.

The Ontario rubber modified asphalt demonstration projects (eight of the eleven projects) have focused on generic dry process RUMAC. The experience with CRM in cold in-place recycling (RUMCIP) for the two projects involved (Grey CIP and Lambton) does not appear encouraging as there were problems with traffic action. The Ontario wet process continuous blending AR project (MTO Wet) has proven to be good, as anticipated from considerable polymer modified HMA experience, and supports further projects based on wet process continuous blending AR.

7.2 ECONOMIC ANALYSIS

The economic analysis of generic dry process RUMAC on a life cycle basis, compared to conventional HMA, presented in Section 4, is unfavourable, even with significant incentives. This is comparable to AASHTO, Rouse and FHWA/EPA findings (Steiner, 1993; Rouse, 1993a; FHWA/EPA, 1993). The economics of CRM use in RUMAC will only become favourable with incentives if long-term performance studies show improved RUMAC functional serviceability over conventional HMA, which is considered unlikely at the time from the short-term performance information available.

An economic analysis of CRM use in cold in-place recycling (RUMCIP) was not completed given both the poor initial performance and lack of costing data.

The economic analysis of wet process continuous blending AR on a life cycle basis, compared to conventional HMA, is potentially quite favourable, provided there is a decrease in maintenance requirements and/or extended service life. US proponents of AR indicate that this should be the case (ARPG, 1989; International Surfacing, 1992; Rouse 1993a.,b.), and the Metro Toronto Transportation AR long-term performance experience and Ontario AR project (MTO Wet) short-term performance experience support this.

7.3 ASPHALT TECHNOLOGY RESEARCH AND DEVELOPMENT NEEDS

The Ontario research and development needs for CRM use in AR and RUMAC are similar to those identified in Subsection 2.8 during the review of rubber modified asphalt technology.

7.4 ENVIRONMENTAL

Air Emissions and Worker Exposures

The results of the Ontario projects indicated similar air emissions and worker chemical exposures for both conventional HMA and RUMAC processes. Studies done elsewhere, primarily the United States, also found no discernible difference between air emissions or worker exposures of conventional HMA and RUMAC or AR. Data from both the Ontario and U.S. studies were not sufficient to make statistical comparisons, however, the air emission data for conventional HMA, RUMAC and AR overlapped and all exhibited a wide variability.

Worker exposure studies in Ontario and the U.S. both measured levels at or below detection limits for the chemicals of concern. On occasion, levels of particulate and benzene solubles exceeded established limit values in the U.S. studies which covered both conventional HMA, RUMAC and AR. On only one occasion was particulate exceeded in the Ontario studies, which covered only conventional HMA and RUMAC. Benzene solubles were non-detectable in the Ontario studies.

Waste Management

Information from Ontario and the U.S. is insufficient to characterize the solid and liquid wastes generated from the use of rubber modified asphalt. The two issues of solid waste leachate and liquid effluent quality have not been characterized for rubber modified asphalt. These issues have not been investigated as they are considered secondary to the air emissions.

8. OUTSTANDING ISSUES AND RECOMMENDATIONS

8.1 ASPHALT TECHNOLOGY AND PAVEMENT PERFORMANCE

The outstanding RUMAC and AR asphalt technology and pavement performance research and development needs were identified in Subsections 2.8, 3.7 and 7.1. These can be summarized as:

Generic Dry Process RUMAC

1. Determine, and document in a user design guide, the optimal type, compatibility with asphalt cement, gradation, composition and amount of CRM for representative generic dry process RUMAC mixes, including mix design procedures. This would be best accomplished through laboratory evaluations that include performance-related factors such as aging, moisture sensitivity, permanent deformation, fatigue cracking and low temperature cracking.

2. Determine, and document in a user specification guide, the most appropriate materials selection and production, placement and compaction techniques for a representative range of generic dry process RUMAC binder and surface course mixes. An example draft special provision for RUMAC is given in Appendix D, that could be extended as the requisite asphalt technology is determined.

3. Determine the long-term performance of the ‘optimal’ generic dry process RUMAC mixes produced, placed and compacted with the most appropriate technology. This will take considerable time and require laboratory performance characterization, accelerated pavement testing and monitoring of the prototype pavement sections. This might best be accomplished by participating, if possible, in the FHWA Phase 2 Program. Regardless, any future major demonstration projects should follow a systematic development, monitoring and evaluation plan such as that outlined in Appendix E.

4. Extend the life cycle cost comparisons of generic dry process RUMAC with conventional HMA as long-term performance data are developed from prototype pavement sections performance monitoring.

Wet Process Continuous Blending of AR

1. Evaluate, with technology transfer, the wet process continuous blending of AR (Florida, Arizona and California, for instance) for a range of dense- and open-graded hot-mix asphalt types. This might be best accomplished through direct technology transfer interaction with the Florida Department of Transportation.

2. Evaluate the performance of the 1977 to 1980 Metro Toronto Transportation AR paving projects (and MTO, as appropriate), and available US AR experience, to extend the life cycle cost comparisons of wet process continuous blending AR HMA with conventional HMA.

RUMAC and AR

Evaluate, and document in a user testing guide, the available mix design, quality control and quality assurance test procedures for generic dry process RUMAC and wet process continuous blending AR.

RUMAC, RRUMAC, AR and RUMCIP

1. Monitor winter snow and ice development, and its control, this winter for the demonstration projects (including control sections) to see if there is any CRM impact on ice control.

2. Monitor the frictional properties (spring and fall) of the demonstration projects (including control sections) to check if there is any CRM impact on frictional properties.

3. Complete overall visual performance assessments each year (spring and fall) for the demonstration projects so that the current findings and experience can be extended. A systematic approach, with an experienced pavement engineer monitoring all of the sections, is recommended.

RUMCIP

The CRM modified cold in-place asphalt recycling (RUMCIP) demonstration projects should be monitored to check the overall technical suitability of this process. It is recommended that a core evaluation program be undertaken to determine if the CRM is beneficial to the cold in-place recycled asphalt performance, or simply acting as an unbound ‘rubber aggregate’.

8.2 RECYCLABILITY

The only outstanding issue concerning the recyclability of RUMAC is the potential impact on the asphalt cement and mix properties associated with repeated recycling, as many surface course mixes will be recycled several times over the life of the pavement before reconstruction. There does not appear to be any leachate problem associated with reclaimed RUMAC in stockpiles as it is similar to RAP (Thompson and Haas, 1992). However, it is very important that the CRM does not impair the reported recyclability of RUMAC and AR mixes. As indicated in Subsection 2.8, this could be readily checked in both the laboratory and field through repeated recycled RUMAC (RRUMAC) production and characterization testing.

8.3 GENERAL CRM ASPHALT TECHNOLOGY AND INTERACTION WITH USERS

At present, it appears that the various MOEE incentives, mainly financial with some technical, are an important factor supporting the current Ontario use of generic dry process RUMAC and RUMCIP. There has only been one wet process continuous blending AR demonstration project, and this was completed by the MTO. These incentives must continue to be significant enough to overcome the paving industry’s current perceived problems and scepticism with the use of recycled scrap tire rubber in hot-mix asphalt, such as: need for a thorough research and testing program to support CRM use; availability of Ontario CRM; best approach, AR or RUMAC?; need for AR and RUMAC specifications based on agency-industry interaction; questioning of long-term pavement life and performance; and recyclability of AR and RUMAC (Sidlar, 1991). It is important that developments addressing these concerns be communicated to the construction industry through Ontario Road Builders Association (ORBA) and Ontario Hot Mix Producers Association (OHMPA) interaction.

The perceived asphalt technology problems inhibiting the use of rubber modified asphalt have been outlined above from an ORBA and OHMPA perspective, that is probably shared by many potential user agencies. The technical resolution of these problems (noting that recyclability has been dealt with) was covered in Subsections 2.8 and 8.7. It is important that the MOEE, in conjunction with the MTO, consultants, testing companies and the paving industry, address the remaining technical problems if CRM use in asphalt paving is to be fostered. A centre or group of excellence approach to researching and resolving these CRM problems and issues is suggested (Blackwell, 1992). It is recommended, in order for the research and resolution to be timely and cost effective, to continue interacting closely with the FHWA, and it is suggested this could include direct financial and logistical participation in the Phase 2 program on CRM use in asphalt (Lord, 1993).

User friendly documentation of CRM use in asphalt, developed to address the problems, and training programs for potential user agencies, consultants and contractors are also recommended.

A number of demonstration projects have taken place late in the paving season, which is not technically desirable. It is suggested that the MOEE and proponents plan demonstration projects with a view to completing projects during the summer paving season.

8.4 ENVIRONMENTAL

Although the air emissions data are not of sufficient quality to make statistical comparisons, general trends of the US and Ontario studies indicate that emissions are similar for conventional, HMA, RUMAC and AR processes. The air emission data for conventional HMA, RUMAC and AR overlapped and all exhibited a wide variability. The wide variability is believed to be influenced by plant operation and maintenance practices and not because of differences due to the use of rubber modified asphalt.

For five of the six rubber modified asphalt demonstration projects where emission testing was completed, MIBK was emitted during RUMAC production and either not detected or orders of magnitude lower during conventional HMA production. In sufficient quantities, MIBK is a skin and mucous irritant and moderately toxic by inhalation but is not considered a carcinogen. The significance, if any, of these MIBK emissions should be assessed.

In addition to the process stack emissions, proper operation and in turn environmental performance should also address fugitive emissions and odours. These two issues are important to asphalt production in general and are not restricted to only rubber modified asphalt. Studies to date on rubber modified asphalt have not addressed odours or fugitive emissions.

As previously stated, the two issues of solid waste leachate and liquid effluent quality have not been characterized for rubber modified asphalt.

Available asphalt technology whether conventional HMA, RUMAC or AR, is capable of meeting environmental regulatory criteria provided it is designed, managed and operated properly. The Ontario studies and US studies show that environmental compliance is feasible, however, industry experience also shows that improper operation can result in non-compliance. This applies to air emissions, solid waste, liquid effluents and occupational health.

This matter of environmental compliance is a regulatory issue under the jurisdiction of the Ontario Ministry of the Environment and Energy. Certificates of Approval - Air for asphalt plants are used as a mechanism to regulate the industry. If a change to RUMAC or AR from conventional HMA required a submission for an amended Certificate of Approval for a plant, this new submission would be considered a deterrent.

Streamlined permitting approaches for a change to RUMAC or AR may include:

- exemption from amended approvals (regulatory change);
- permit-by-rule approvals (regulatory change); and
- amended approvals by asphalt plants likely to be involved in the use of RUMAC and AR to be obtained well in advance of commencement of scheduled operation.

9. CONCLUSIONS

The eleven Ontario rubber modified asphalt demonstration projects have been evaluated in terms of pavement performance and environmental impacts, including recyclability, with comparison to the findings of other jurisdictions such as the United States Federal Highway Administration and Environmental Protection Agency. The demonstration projects included: eight rubber modified asphalt concrete (RUMAC) projects in which the recycled rubber from scrap tires (termed crumb rubber modifier, CRM) behaves essentially as rubber aggregate (termed dry process), including one project with recycled rubber modified asphalt concrete (RRUMAC); two rubber modified cold in-place recycling projects (RUMCIP); and one rubber modified asphalt cement (AR) project (termed wet process).

The Ontario generic dry process rubber modified asphalt concrete (RUMAC) and wet process continuous blending asphalt rubber (AR) pavement performance and environmental impacts, including recyclability, findings are very similar to those of the Federal Highway Administration/Environmental Protection Agency (FHWA/EPA) who also considered two of the Ontario rubber modified asphalt demonstration projects (Thamesville Phase I and Haldimand-Norfolk Trial 1). On the basis of early short-term performance monitoring experience for eight projects, there is no reason why the quality and performance of properly designed and placed generic dry process RUMAC cannot be equivalent to conventional hot-mix asphalt (HMA). This will require care in: the selection of CRM type, compatibility, grading, composition and content; the modified Marshall method of RUMAC mix design; and the production, placement and compaction of the RUMAC during favourable paving conditions. It should be noted that the comparative pavement performance of RUMAC surface course mixes with relatively high and coarse CRM content has been very poor to poor. For this reason, finer CRM (No. 10 mesh, or finer) has been used at the 1.0 to 1.5 percent addition level in many of the more recent generic dry process RUMAC demonstration projects.

The wet process continuous blending of AR shows considerable promise, based on early (1977 to 1980) and current (Highway 400 test section) Ontario and State (Florida, for instance) experience, and should certainly be pursued. It appears that AR can enhance the durability of dense- and open-graded hot-mix asphalt. One State (California) has developed an asphalt rubber hot mix gap-graded (ARHM-GG) interim guide which included thinner structural design equivalents. The use of AR in open- and dense-graded friction course, SAM and SAMI applications should also be considered. The wet process continuous blending of AR in Ontario might be best established through technology transfer from the Florida Department of Transportation.

The use of CRM in cold in-place recycling (RUMCIP) cannot currently be considered a technical success as extensive rutting and ravelling were experienced for the two demonstration projects before the placement of the conventional HMA wearing surface. This technology should be checked through a core evaluation program. Economic analyses were not completed on RUMCIP.

The one project (Thamesville Phase II) with the recycling of generic dry process RUMAC (RRUMAC), and the FHWA/EPA findings, indicate no technical problems with the recyclability of RUMAC. It also appears, from the FHWA/EPA study, that there should be no technical problems with the recyclability of AR. However, there is some question concerning the accumulative influence of repeated recycling of RUMAC and AR on mix quality that should be addressed through laboratory and plant testing. While considered unlikely, if any rubber modified asphalt is eventually unsuitable for recycling due to technical or supply factors, there could be significant disposal costs involved.

The economics (life cycle cost) of generic dry process RUMAC binder and surface course pavement use, compared to conventional HMA pavements, does not appear to be favourable, even with waste management incentives, based on Ontario experience and costing. Given the paucity of long-term performance data, the life cycle cost analyses for generic dry process RUMAC must be considered to be preliminary at this time.

The economics (life cycle cost) of wet process continuous blending AR was considered by extending US experience and costing to Ontario for typical surface course pavement. If the incorporation of AR does decrease maintenance cost and/or extend the service life, as anticipated, then there is certainly a potential for considerable savings through this CRM use. This is the position that has been taken by US supplier proponents and several States (Arizona, Florida and California, for instance).

The air emission test results of the conventional HMA and RUMAC processes overlapped and exhibited a wide variability indicating that, except for the compound 4-methyl-2-pentanone (otherwise known as methyl isobutyl ketone or MIBK), there was no discernable difference between the emissions of the two processes. The wide variability is believed to be influenced by plant operation and maintenance practices and not because of differences due to the use of rubber modified asphalt. However, in five of the six demonstration projects where emission testing was conducted, MIBK was emitted during RUMAC production and either not detected or orders of magnitude lower during conventional HMA production.

Occupational health exposures monitored for the two processes also measured overlapping levels that, in most instances, were at or below the detection limits for the compounds of interest. Worker exposures for the two processes of conventional HMA and RUMAC were similar.

The two issues of solid waste leachate and liquid effluent quality have not been characterized for rubber modified asphalt. Although it is believed that these wastes are similar to conventional HMA, until this characterization is undertaken for rubber modified asphalt processes these issues will continue to be raised.

Available asphalt technology whether conventional HMA, RUMAC or AR, is capable of meeting environmental regulatory criteria provided it is designed, managed and operated properly. This applies to air emissions, solid waste, liquid effluents and occupational health.

The Certificates of Approval - Air issued by the Ontario Ministry of Environment and Energy for asphalt plants are used as a mechanism to regulate the environmental performance of the industry. Presently, the asphalt industry considers this permitting process to be restrictive and would consider further permitting for RUMAC or AR to be a deterrent to its application. Joint industry/government discussions on rubber modified asphalt technology and its application in Ontario should be undertaken to resolve these permitting issues.

It is recognized that technical issues still require resolution to optimize the application of rubber modified asphalt technology and that further development will be undertaken in areas such as long-term performance. During this research, the environmental component should not be overlooked when appropriate.

Several asphalt technology and environmental recommendations are given in the areas of: CRM selection; generic dry process RUMAC placement; RUMAC long-term performance; life cycle cost comparisons; wet process continuous blending of AR; test procedures for AR and RUMAC; influence of repeated RUMAC recycling; multiple stack emission tests; potential odour problems; and pavement and recycled RUMAC leachability. The centre of excellence concept, and close interaction with the FHWA, are suggested for dealing with the asphalt technology recommendations. It is important that user agencies, the Ontario Road Builders Association, the Ontario Hot Mix Producers Association and pavement consultants be kept informed, and involved, in the development of CRM use in asphalt paving in Ontario.

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APPENDICES

APPENDIX A

TERMINOLOGY

This summary of terminology is for the non-specialist and should not be considered technically complete. An extensive compilation of standard technical definitions is available from ASTM (ASTM, Compilation of ASTM Standard Definitions, 7th Edition, American Society for Testing and Materials, Philadelphia, 1990)

aggregate:	granular material of mineral composition, such as sand, gravel or crushed stone, used in construction.
ambient (ambient process):	crumb rubber production process that crushes the scrap tire to the desired particle size at ambient temperature.
acid gases:	refer to inorganic acids in the emission gases such as hydrogen chloride, hydrogen bromide and hydrogen fluoride.
antistripping additive:	additive to alleviate stripping potential of an asphalt concrete (physical separation of asphalt cement from aggregate, primarily due to moisture action).
Arm-R-Shield^{TM}:	trade name of Arizona Refining Company for an asphalt rubber binder comprising about 20 percent crumb rubber (20 to 40 percent devulcanized and 60 to 80 percent ambient process vulcanized, all minus 425 μm sieve size), 2 to 4 percent extender oil and 76 to 78 percent asphalt cement, with blending performed at 190 to 220°C. (Originally patented by Union Oil Company.)
aromatic (aromatic oil):	arene class of hydrocarbons such as benzene, naphthalene or anthracene (aromatic hydrocarbons).
asphalt:	dark brown to black cementitious material in which the predominant constituents are bitumens that occur in nature or are obtained during crude petroleum refining.
asphalt cement (AC):	asphalt that is refined to meet specifications for paving, industrial and special purposes.
asphalt concrete:	plant hot mixture of asphalt cement and well-graded aggregate (HMA), placed and compacted into a dense mat in construction of asphalt pavement.
asphalt pavement:	pavement consisting of surface and binder course asphalt concrete on supporting courses such as concrete base (composite pavement), asphalt treated base, cement treated base, granular base and/or granular subbase placed over the subgrade.

asphalt rubber (AR):	asphalt cement modified by the addition of a crumb rubber modifier (CRM). (Also refers to a specific use or application of asphalt rubber, for example, asphalt rubber binder, asphalt rubber hot-mix, asphalt rubber pavement, etc.).
base course:	layer of material immediately beneath the asphalt concrete or portland cement concrete surface of a pavement.
binder:	substance used to hold particles together or to a substrate. (Usually an organic material such as asphalt cement.)
binder course:	the lower asphalt concrete course(s) of a pavement.
buffings (tire buffings):	high quality fine tire rubber which is a byproduct from the conditioning of tire carcasses in preparation for retreading.
byproduct:	secondary or incidental product to primary production material.
chlorobenzenes:	class of compounds which includes chlorine substituted benzenes (C_6H_6), where chlorine replaces one or more of the hydrogen atoms.
chlorobiphenyls:	class of compounds which includes chlorine substituted biphenyls (C_6H_5-C_6H_5), where chlorine replaces one or more of the hydrogen atoms (includes polychlorinated biphenyls, or PCBs).
chlorophenols:	class of compounds which includes chlorine substituted phenols (C_6H_5OH), where chlorine replaces one or more of the hydrogen atoms.
chunk rubber:	experimental, coarse crumb rubber (minus 12.5 mm to plus 4.75 mm sieve size) modified gap-graded hot-mix asphalt (gap-graded RUMAC) being evaluated by Cold Regions Research and Engineering Laboratory (CRREL).
coal tar pitch volatiles:	various organic soluble compounds measured according to NIOSH Method 5023. Also referred to as cyclohexane solubles and benzene solubles and includes anthracene, benzanthracene, benzo(a)pyrene, carbazole, phenanthrene and others.
coarse aggregate:	aggregate that is predominantly retained on the 4.75 mm sieve size.
cold recycling (cold asphalt pavement recycling):	full or partial depth reuse of old asphalt concrete pavement (can be used for surface treatment, and can include treated and untreated base), that is either processed in-place or at a central plant, typically with the addition of emulsified asphalt (or other additive

	such as cutback asphalt, lime or cement) to achieve desired cold mix quality, followed by placement and compaction.
combustion gases:	standard products of a combustion process. Includes carbon dioxide, carbon monoxide, oxygen, nitrogen oxides and sulphur dioxide.
concrete (portland cement concrete, PCC):	composite material consisting essentially of a mixture of cement and water (binding paste) with which are mixed particles of fine and coarse aggregates.
continuous blending:	central, or plant, on line production wet process for asphalt rubber.
crackermill:	crumb rubber production process that tears apart scrap tire rubber between rotating corrugated steel drums, typically to a minus 4.75 mm to plus 425 μm sieve size.
crumb rubber:	scrap tire rubber that has been processed to a sieve size usually less than 9.5 mm. (Sometimes referred to as ground tire rubber.)
crumb rubber modifier (CRM):	general term for scrap tire rubber that has been reduced in size (processed) and is used as a modifier in asphalt materials.
crushed gravel:	aggregate, from crushing of gravel, with substantially all particles having at least one fractured (crushed) face.
crushed stone:	aggregate, from crushing of quarried rock, with all faces fractured (crushed).
cryogenic (cryogenic process):	crumb rubber production process that freezes the scrap tire rubber and crushes it to the desired sieve size. (Typically using liquid nitrogen and proprietary technology, for example, Recovery Technologies Inc.)
dense-graded (well-graded):	uniformly graded from the maximum aggregate size down to mineral filler.
devulcanized rubber:	tire rubber treated by heat, pressure and the addition of softening agents to alter the properties of the rubber.
diluent:	light petroleum product (typically kerosene) added to an asphalt rubber binder just before the binder is spray-applied to a pavement surface.
dose-response relationship:	the relationship between the dose of a chemical and the incidence or severity of adverse effect.
dry process:	any method that involves mixing the crumb rubber modifier (CRM) directly with the aggregate, either before (typically) or after the addition of asphalt cement, during hot-mix asphalt (HMA) production.

EcoflexTM:	storable asphalt rubber binder developed by Bitumar Inc. (Montreal) comprising 10 percent crumb rubber (minus 4.00 mm sieve size) ‘dissolved’ into 90 percent asphalt cement.
emission factor:	measure of the amount of contaminant released for a specific process. Expressed as the mass of contaminant released to the environment per mass of final product produced.
emulsified asphalt:	anionic or cationic emulsion of asphalt cement and water that contains a small amount of an emulsifying agent, which sets by water separation/evaporation and/or chemically, leaving the asphalt cement to perform its cementing function.
extender oil:	an aromatic oil used to supplement the crumb rubber modifier-asphalt cement reaction. (Typically provides oil to reduce viscosity and to replace oils absorbed by the crumb rubber modifier.)
fine aggregate:	aggregate that predominantly passes the 4.75 mm sieve size and is retained on the 75 μm sieve size.
Flexochape^{TM}:	storable asphalt rubber binder developed by French Beugnet Group (BAS Recycling, Inc. in United States) comprising (typical formulation) 10 percent crumb rubber (minus 850 μm sieve size), 6 percent extender oil, 2.5 percent synthetic elastomer catalyst and 81.5 percent 80/100 penetration asphalt cement, with blending at 180°C.
flushing:	excess asphalt cement at the surface of an asphalt pavement.
flux oil:	thick, relatively nonvolatile fraction of petroleum which may be used to soften asphalt to a desired consistency.
friction course:	surface course asphalt pavement in which the aggregates and mix are selected for optimal frictional properties, can be dense-graded or open-graded.
full depth recycling:	full thickness of old asphalt concrete or concrete (PCC) is processed and recycled.
gap-graded:	gradation in which one, or more, aggregates size fraction(s) is not included.
generic dry process:	a dry process method using crumb rubber modifier, generally minus 2 mm mesh size, that is mixed with either dense-graded, open-graded, or gap-graded aggregates to provide rubber aggregate, and somewhat modify the asphalt cement, in hot-mix asphalt.

granulated CRM:	cubical, uniformly shaped, cut crumb rubber particles with a low surface area, that are generally produced by a granulator.
granulator:	crumb rubber production process that shears apart the scrap tire rubber, cutting the rubber with revolving steel plates that pass at close tolerance, reducing the size to generally minus 9.5 mm to plus 2.00 mm sieve size.
gravel:	granular material consisting of rounded, water-worn rock fragments 2 mm to 75 mm in size usually intermixed with sand.
ground CRM:	irregularly shaped, torn crumb rubber particles with a large surface area, that are generally produced by a crackermill.
hammermill:	crumb rubber production process (typically cryogenic) that uses the impact attrition and shearing action of a hammermill crusher, typically to a minus 4.75 mm to plus 4.25 µm sieve size.
hot asphalt pavement recycling (hot-mix recycling, recycled hot mix, RHM):	removal (surface milling or full depth) of old asphalt concrete (reclaimed asphalt pavement, RAP), processing, heating and mixing in a hot-mix plant (batch, drum or drum/batch) with new aggregates and new asphalt cement (softer grade or with recycling agent), relaying and compacting to meet specifications for conventional hot-mix asphalt concrete (HMA).
hot-mix asphalt concrete (hot mix, hot-mix asphalt, HMA):	designed aggregate and asphalt cement mix produced in a hot-mix plant (batch, drum or drum/batch) where the aggregates are dried, heated and then mixed with heated (fluid) asphalt cement (hot mix), then transported, placed and compacted while still at an elevated temperature (about 125 to 135°C) to give a durable, deformation resistant, fatigue resistant pavement course.
hot in-place recycling (asphalt pavement surface recycling):	hot reworking of the surface of an aged asphalt pavement (typically up to 50 mm) using preheaters and a heat reforming machine, typically with the addition of a rejuvenator, aggregate or new hot mix (HMA) to restore the condition of the scarified old asphalt pavement, and sometimes with an integral surface course overlay, all suitably placed and compacted in a single or multi-pass process.
inert particulates:	refer to unreactive solids present in the emission gases. (Regulation 346 of Ontario's Environmental Protection Act further defines suspended particulate matter as being particulates less than 44 microns in size.)
job mix formula (JMF):	selected asphalt cement content and aggregate gradation for an asphalt mix, based on mix design procedure.

latex:	‘milky’ colloid in which natural or synthetic rubber is suspended in water.
leachate testing:	a measure of the extent to which hazardous components are emitted from a tested material into a liquid medium.
light ends:	lower viscosity components of an asphalt cement.
lime:	all classes of calcitic (high calcium) and dolomitic quicklime and hydrated lime.
manufactured sand:	fine aggregate produced by the crushing and processing (does not include screenings) of quarried rock or boulders, cobbles and gravel from which the natural fine aggregate has been removed.
McDonald method:	asphalt rubber binder developed by McDonald (including ARCO and Sahuaro) incorporating (typical formulation) 15 to 25 percent crumb rubber (minus 2.00 mm sieve size), with reaction usually performed for about 45 minutes at 190 to 205°C.
micro-mill:	crumb rubber production process that further reduces the size to a very fine ground particle below a 425 μm sieve size.
milling (cold planing):	removing surface of an asphalt concrete pavement, using a travelling machine equipped with a transverse rotating cutter drum (milling head with tips), typically 25 to 75 mm in depth. The resulting asphalt concrete millings (form of reclaimed asphalt pavement, RAP) are usually recycled.
mineral filler:	finely divided mineral product, at least 70 percent of which passes the 75 μm sieve size (hot-mix asphalt use), such as pulverized limestone (most common manufactured filler). (The term ‘filler’ is often used with hot-mix asphalt for all of the minus 75 μm sieve size material.)
Modified Method 5 Sampling Train:	sampling for particulate material and metals is carried out isokinetically using a modified MOEE Method 5/CARB Method 436 sampling train identified as the Modified Method 5 Train. The standard MOEE Method 5 train consists of two water impingers, followed by an empty impinger and finally a silica gel impinger. The standard CARB Method 436 multiple metals sampling train consists of two nitric acid/hydrogen peroxide impingers followed by two potassium permanganate/sulphuric acid impingers and finally a silica gel impinger. (The Modified Method 5 Train used for the subject emission testing programs contained the same impinger configuration as the standard CARB Method 436 multiple metals sampling train.)

open-graded:	gradation containing little or no fine aggregate and mineral filler and/or in which the void spaces are relatively large.
Overflex^{TM}:	asphalt rubber binder developed by Sahuaro Petroleum and Asphalt Company incorporating about 20 percent crumb rubber, generally without extender oil or other additives. (See McDonald method.)
pavement structure:	all courses (components) of a pavement above the subgrade to the traffic surface such as granular subbase, granular base, treated (asphalt or cement) base, asphalt concrete (HMA) and concrete (PCC).
permissible exposure limits:	regulated airborne concentrations of hazardous substances above which workers should not be exposed.
plastic:	polymeric materials that can be made to flow under stress.
PlusRide^{TM}:	dry process method developed in Sweden (Rubit^{TM}) that incorporates 2 to 3 percent, by mass of hot-mix asphalt, coarse crumb rubber (1 mm to 7 mm sieve size) in a gap-graded mix.
polymer:	material made of 'giant' molecules formed by the union of simple molecules (monomers), for example polymerization of ethylene forms a polyethylene chain.
pressure reaction method:	wet process method involving the preblending of crumb rubber in hot asphalt cement, followed by a pressure reaction system, to achieve reaction times considerably less than 15 minutes. (The processing equipment will be available through Modified Asphalt Systems, Inc.)
reaction:	interaction between crumb rubber modifier and asphalt cement when blended together. The reaction, more appropriately defined as polymer swell, is due to the absorption of aromatic oils from the asphalt cement into the polymer chains of the crumb rubber. (It is not considered to be a chemical 'reaction'.)
reclaimed aggregate material (RAM):	removed and/or processed pavement materials containing no reusable asphalt cement.
reclaimed asphalt pavement (RAP):	removed and/or processed pavement materials containing asphalt cement and aggregates.
recycling:	when material is reclaimed from the waste stream and put to some use after varying degrees of processing.
recycled hot mix (RHM):	hot-mix asphalt concrete that contains processed reclaimed asphalt pavement (RAP). (See hot asphalt pavement recycling.)

risk assessment:	the qualitative or quantitative characterization of the potential adverse effects of a chemical on human health or the environment.
rubber:	elastomeric materials (natural and synthetic) such as latex and reclaimed rubber from scrap tires. These materials exhibit elastic recovery.
rubber aggregate:	crumb rubber modifier, added to hot-mix asphalt (asphalt concrete) using the dry process, that essentially retains its physical shape and rigidity.
rubber modified asphalt concrete (RUMAC):	hot-mix asphalt (asphalt concrete) which incorporates crumb rubber modifier primarily as rubber aggregate.
sand:	fine aggregate resulting from natural disintegration and abrasion of rock or processing of completely friable sandstone. (See manufactured sand and screenings.)
scrap tire:	tire that can no longer be used for its original purpose.
screenings:	fine aggregate including dust (minus 75 μm) produced by the crushing of quarried rock or boulders, cobbles and gravel from which the natural fine aggregate has been removed. (Typically a byproduct of crushing and processing quarried rock or gravel for asphalt and concrete coarse aggregates.)
shredding:	scrap tire size reduction process that reduces scrap tires to pieces 0.15 m^2 and smaller.
sludge:	material in the form of a concentrated suspension of solids in liquid.
solid waste management:	conduct and regulation of the entire process of generation, storage, collection, transportation, processing, reduction, reuse, recovery and disposal of solid waste.
stone:	any natural rock deposit or formation of igneous, sedimentary and/or metamorphic origin, usually used as dimension stone or crushed stone in building or road construction.
stress absorbing membrane (SAM):	a surface treatment ('rubberized' chip seal) using an asphalt rubber binder spray application and cover aggregate.
stress absorbing membrane interlayer (SAMI):	a membrane beneath an asphalt concrete overlay, designed to delay the propagation of cracks through the new overlay. The membrane is often a spray application of asphalt rubber binder with cover aggregate.
subbase course:	layer of material in a pavement immediately above the subgrade.

subgrade:	soil prepared through cut, fill and/or fine dressing to support a pavement.
surface course:	top hot-mix asphalt course (HMA) of a pavement, sometimes called asphalt wearing course.
sustainable development:	using natural resources in such a way as to meet current economic and social needs, but not depleting or degrading these resources to the point that they cannot meet these needs for future generations.
trace metals:	include aluminum, antimony, arsenic, barium, beryllium, bismuth, boron, cadmium, calcium, chromium, cobalt, copper, iron, lead, lithium, magnesium, mercury, molybdenum, nickel, phosphorus, potassium, rubidium, selenium, silicon, silver, sodium, strontium, sulphur, tellurium, thallium, tin, titanium, vanadium, zinc and zirconium. They are generally present in the emission gases in the form of metal oxides.
total petroleum hydrocarbons:	refer to organic compounds containing predominantly carbon and hydrogen, which are derived from petroleum.
unbound aggregate:	compacted aggregate layer(s) in pavement structure that does not contain a binder (asphalt cement, for instance).
unsaturated zone:	the soil zone above the water table.
volatile organic compound (VOC):	any organic chemical compound which can participate in an atmospheric photochemical reaction, other than those specifically designated as having negligible reactivity, is considered to be a volatile organic compound. The official Environment Canada definition of a VOC includes a list of the following exempt compounds: methane, ethane, methyl chloroform, methylene chloride, CFC-113 (trichlorotrifluoroethane), CFC-114 (dichlorotetrafluoroethane), CFC-115 (chloropentafluoroethane), CFC-11 (trichlorofluoromethane), CFC-12 (dichlorodifluoromethane), CFC-22 (chlorodifluoromethane), CFC-23 (trifluoromethane), HCFC-123 (dichlorotrifluoroethane), HCFC-141b (dichlorofluoroethane), HCFC-142b (chlorodifluoroethane), and HFC-134a (tetrafluoroethane).
waste:	wide variety of materials which are discarded or rejected as being spent, useless, worthless or in excess.
wet process:	any method that blends a crumb rubber modifier with an asphalt cement prior to incorporating this asphalt rubber binder in an asphalt mix or treatment.

APPENDIX B

PROJECT TECHNICAL DATA

B1. GENERAL

The available technical, environmental and monitoring data for each project have been summarized, along with the results of current (September 1993) monitoring by JEGEL, in Project Technical, Environmental and Monitoring Data Sheets which are given in Appendices B-2 through B-12 (same order as the MOEE and adopted for the General References). The available information for each project has been incorporated into these data sheets, in as much detail as possible, including the project mix design information, ranges and/or mean results of testing during production, environmental testing methods and protocols and results of any monitoring up to 1993. Each project was reinspected by JEGEL in September 1993, and these monitoring results and selected photographs for each project are also presented.

It should be noted that the following information was not available for most demonstration projects:

- hours of operation
- pavement design life
- aggregates physical properties test data (petrographic analyses, Micro-Deval soundness, percent crushed particles, etc.)
- crumb rubber modifier moisture content and chemical properties
- process control testing of hot-mix aggregates.
- details on trucks, pavers and rollers
- post-construction pavement testing - smoothness for instance
- hot-mix production - materials consumed and general observations
- costing data, including unit costs, costs of quality control and quality assurance testing, plant modifications, emissions controls, etc.
- monitoring for winter snow and ice development, and removal
- monitoring of frictional properties

A recommended guide work plan for the evaluation of future crumb rubber modifier (CRM) major demonstration projects is given in Appendix E.

NOTE: Abbreviations used in Appendix B.

CC = Custom Cryogenic
NP = Not Provided
UN = Unknown

NA = Not Applicable
RT = Recovery Technologies
t = tonnes

[Grey #1]

B2. COUNTY OF GREY ROAD #12

PROJECT TECHNICAL DATA SHEETS

Project: County of Grey Road #12

Date Completed: Phase 1: November 14, 1991
Phase 2: May 4 to 19, 1992
July 15 to 24, 1992

Location: County Road #12 from Highway 6 to Markdale for 12.5 km

Agency: County of Grey Highways Department

Consultants/Designers: Chapman Group/Church and Trought/Grey County

Contractor: The Murray Group

Plant: Oil-fired batch with dry collector; CRM in polymelt bags conveyed to weigh hopper.

Mix Types: HL 4 and HL 4 RUMAC

Tonnage Placed: HL 4: NP HL 4 RUMAC: 8769 t

CRM Source: Baker Rubber Company Type: Ambient
No. 10 mesh

CRM Used: 134,720 kg (33,000 tire equivalents)

CRM Gradation:

	Percent Passing						
	4.75 mm	2.36 mm	1.18 mm	600 µm	300 µm	150 µm	75 µm
Specified		100	45-55	25-35	8-12		
Production	100.0	97.1-100.0	39.4-45.0	29.5-36.8	4.4-9.8	0-1.8	0-0.2

Mix Design Proportions:

	HL 4	HL 4 RUMAC
HL 4 Stone (Murray)	NP	44.5
Asphalt Sand (Murray)	NP	41.0
Stone Sand (Murray)	NP	13.0
CRM (Baker)	NP	1.5
Asphalt Cement (McAsphalt 85/100)	NP	6.8

Placement Conditions:
Weather: Sunny, Low 9°C High 20°C, some freezing conditions during November 1991 trial paving.

Paver: Barber Greene BG245
Compaction Train: Static steel drum rollers (2)
Rubber-tired roller (1)

	Laydown Temperature	Thickness, mm	% Compaction
HL 4 RUMAC	140°C-151°C (150°C max specified)	NP	NP

[Grey #1]

TABLE B2-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	HL 4 SURFACE		HL 4 RUMAC		GREY COUNTY HL 4 SPECIFICATIONS
	JMF	Production	JMF	Production	
19.0 mm	NP	NP		100.0	100
16.0 mm	NP	NP	100.0	99.2-100	98-100
13.2 mm	NP	NP	94.9	93.4-98.9	83-95
9.5 mm	NP	NP	78.4	71.7-83.7	62-82
4.75 mm	NP	NP	57.1	50.6-60.5	40.67
2.36 mm	NP	NP	48.7	43.3-54.7	27-66
1.18 mm	NP	NP	40.2	33.1-46.2	16-60
600 µm	NP	NP	31.0	27.5-37.9	8-47
300 µm	NP	NP	18.8	16.3-24.3	4-27
150 µm	NP	NP	7.3	5.8-9.1	1-10
75 µm	NP	NP	4.7	3.2-5.0	0-6
% AC	NP	NP	6.8	6.28-7.29	
% CRM	NP	NP	1.5	1.1-2.1	
Stability, N	NP	NP	9100	8366-9805	8900 min
Flow, 0.25 mm	NP	NP	15.5	13.7-15.0	8 to 20
Air Voids, %	NP	NP	18.1	1.4-3.0	2 to 4
VMA, %	NP	NP			
BRD, kg/m^3	NP	NP	2346	2366-2390	
MRD, kg/m^3	NP	NP	2417	2423-2470	
Recovered Pen	NP	NP		48	

Placement Problems:

CRM gradations generally outside specification limits. Polymelt bagged CRM nominally 45 lb/bag; actually 38 to 47 lb/bag. Occasional pick-up problems due to rubber-tired roller. Mix ‘tenderness’ and hairline cracking observed and the rolling pattern was changed. Some mix segregation was noted and attributed to worn condition of batch plant pugmill mixing blades.

[Grey #1]

PROJECT ENVIRONMENTAL DATA SHEET

Air Pollution Control Equipment: Batch plant with fabric filter dust collector for drier emissions. Pugmill exhaust vent kept open, with no emissions controls.

Air Emission Type: Stack sampling, pugmill exhaust vent.

Plant Type: Batch type mixer, manufacturer not provided. Fuel: #2 Fuel Oil.

Mix Type: HL 4, HL 4 RUMAC

Discharge Temperature: 150° to 160°C typically
Drier Temperature: 180°C max specified

Test Dates (1992):	July 15	July 16	July 24	May 13	May 14	May 15
Production Rates, t/hr:	147.7	161.3	154.5	133.5	131.5	126.9

Air Program:

Compounds Sampled	Sampling Method
Inert Particulates Trace Metals Acid Gases	MOEE Method 5 sampling train with modified impingers as per CARB Method 436
Combustion Gases	Continuous Emission Monitoring by MOEE MAPS Vehicle
Volatile Organic Compounds	Volatile Organic Sampling Train (VOST) USEPA Method 30
Polynuclear Aromatic Hydrocarbons Dioxins and Furans Chlorobiphenols Chlorophenols Chlorobenzenes	Modified MOEE Method 5 Sampling Train

Occupational Health Program: Not Applicable

Waste Program: Not Applicable

Ground and Surface Water Program: Not Applicable

[Grey #1]

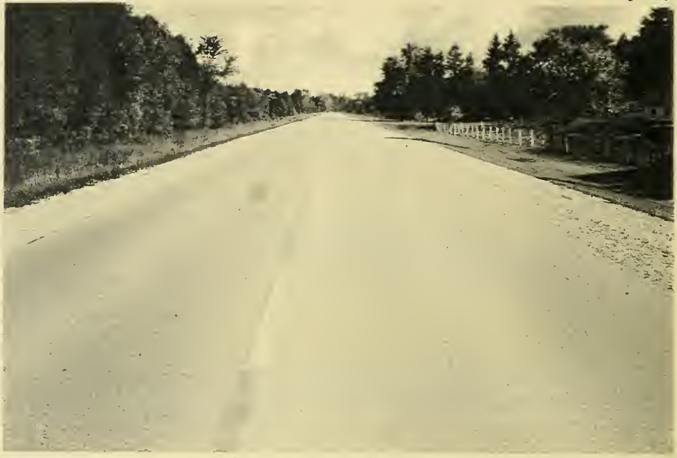
PROJECT MONITORING DATA SHEETS

Current Monitoring: (JEGEL, September 1993)

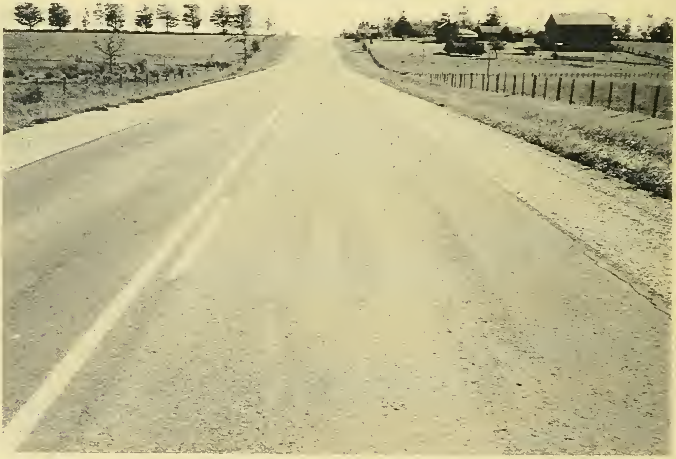
	Grey County HL 4	HL 4 RUMAC
Section	County Road 12 County Road 23 to Markdale	County Road 12 Highway 6 to Markdale
Visual Rating	8.7	8.0
Ride Control Rating	8.5	8.0
General Condition	Very good. Frequent low severity edge cracking and occasional low severity ravelling.	Very good with localized poor areas. Low to medium severity ravelling and coarse aggregate pop-outs in first 250 m east of Highway 6 (Nov/91 paving). Surface texture somewhat variable with 'streaking'. Coarse aggregate pop-outs in ravelled or streaking areas. Generally 'dull' mix appearance.
General Comments		Localized structural failures including alligator cracking, deformations and edge cracking.

Distress Density:

Distress Type	Severity	Length (Area) m (m^2)	Density %	Severity	Length (Area) m (m^2)	Density %
Longitudinal Cracking				L	14	<0.1
Transverse Cracking				L	27	<0.1
Ravelling	L	(5)	<0.1	L	(99)	0.1



PHOTOGRAPH B2-1: Grey County Road 12 Control Section at approximately Station 13+200 looking east. The general condition of this control section place in 1992 is very good. Pavement edge cracking likely caused by vehicles driving near the edge of this relatively narrow pavement is evident along the right side.



PHOTOGRAPH B2-2: Grey County Road 12 HL 4 RUMAC Section at Station 6+600 looking west. The general appearance of this mix placed in the summer of 1992 is very good with localized poor areas. The surface course has a generally dull appearance, and in localized areas, ‘streaking’ and associated ravelling/coarse aggregate popouts are evident as shown in the foreground.

B3. COUNTY OF GREY RUBBERIZED COLD IN-PLACE RECYCLING

PROJECT TECHNICAL DATA SHEETS

Project: County of Grey Rubberized Cold In-Place Recycling

Date Completed: August 14-20, 1992

Location: Grey County Road 13, 5.1 km

Agency: County of Grey Highways Department

Consultants/Designers: Trow/Grey County

Contractor: MSO Construction

Plant: Cold In-Place Paving Train (MSO).

Mix Types: 75 mm of Emulsion-Modified Rubberized Cold In-Place Mix with 50 mm Hot-Mix Asphalt Overlay (HL 4).

CRM Source: Recovery Technologies

Type: Cryogenic
No. 4 mesh

CRM Used: (7,000 tire equivalents)

CRM Gradation: Percent Passing

	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 μm	300 μm
CRM	100.0	97.4	34.5	0.5	0.5	0.4

Mix Design Proportions - Oregon DOT Cold Mix Design Procedure.

	Standard Cold Mix	Rubberized Cold Mix
RAP (Grey County)	100.0	98.0
CRM	-	2.0
Asphalt Emulsion (HF-150)	1.8	1.5

Placement Conditions:
Weather: Overcast, with temperatures between 10°C and 15°C.

Paver: MSO Cold In-Place Recycling Train
Compaction Train: Double steel drum static roller (1)
Rubber tired roller (1)

No compaction test results available.

TABLE B3-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	STANDARD COLD MIX	RUBBERIZED COLD MIX
16.0 mm	100.0	100.0
13.2 mm	97.0	97.0
9.5 mm	83.6	83.6
4.75 mm	60.5	60.5
2.36 mm	46.8	46.8
1.18 mm	37.1	37.1
600 µm	26.0	26.0
300 µm	15.3	15.3
150 µm	8.6	8.6
75 µm	5.0	5.0
% AC	NP	7.01
% CRM		3.0
Stability, N, at 25°C	20795	22000
at 60°C	3945	4500
Flow, 0.25 mm	714	714
Air Voids, %	8.3	9.5
BRD, kg/m^3	2285	2225
MRD, kg/m^3	2490	2452
Recovered Pen		36

Note: No Production Results

Placement Problems:

No obvious problems during cold in-place process placement. However, after being subjected to traffic, severe rutting and ravelling occurred in the rubberized cold in-place section. About 2 km of the 3 km section was milled out and reprocessed in-place adding 2.5 percent HF-150P emulsion. Rutting and ravelling continued to occur after retreatment, requiring a 20 to 25 mm thick hot-mix repair overlay (HL 4). A 50 mm thick HL 4 surface course was placed over the cold in-place sections. (A hot-mix asphalt or surface treatment is placed over cold in-place mix to act as a wearing surface.)

PROJECT ENVIRONMENTAL DATA:

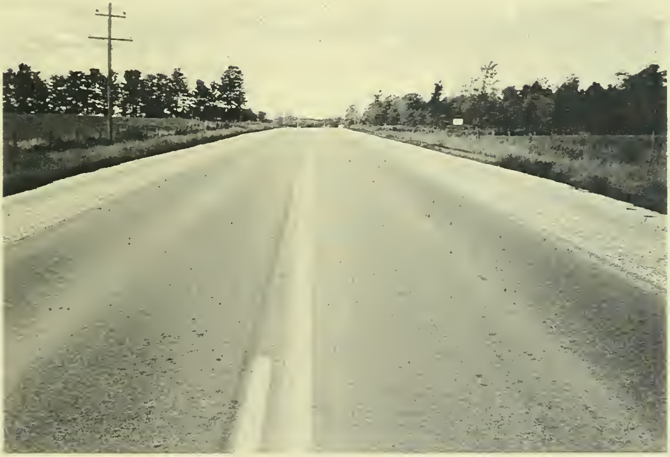
Not Applicable

PROJECT MONITORING DATA SHEET

Current Monitoring (JEGEL, September 1993)

Section	Standard Cold Mix Highway 4 to 900 m North	Rubberized Cold Mix 900 m to Eugena
Visual Rating	9.5	9.5
Ride Comfort Rating	9.5	9.5
General Condition	Excellent low severity edge cracking	Excellent occasional coarse aggregate pop-outs
General Comments	test section reprocessed with additional emulsion as initial mix did not set properly.	

PHOTOGRAPH



PHOTOGRAPH B3-1: Grey County Road 13 approximately 800 m north of Highway 4 looking north. Cold in-place recycling technology was used in this section. The condition of the conventional HL 4 surface course is excellent. Occasional coarse aggregate popouts can be seen in the foreground.

B4. GROW-RICH COMPOSTING FACILITY

PROJECT TECHNICAL DATA SHEETS

Project: Grow-Rich Composting Facility   Date Completed: November 2 to 10, 1992

Location: Sarner Road, Niagara Falls, Ontario, 3.5 acres of composting facility paving.

Owner: Grow-Rich Inc.   Consultants/Designers: Quentin Chapman/Church and Trought/Grow-Rich

Contractor: Hard Rock Paving Co.   Plant: Gas-fired batch with dry collector.

Mix Types: HL 3 RUMAC and HL 8 RUMAC

Tonnage Placed: HL 3 RUMAC: 1239 t   HL 8 RUMAC: 1619 t

CRM Source: Recovery Technologies   Type: Cryogenic
No. 20 mesh, No. 10 mesh

CRM Used: 61700 kg (16,000 tire equivalents)

CRM Gradation	Percent Passing					
	2.36 mm	1.18 mm	600 μm	300 μm	150 μm	75 μm
HL 3 CRM Production		100.0	60.8±0.5	18.7±1.6	4.4±0.2	1.3±0.2
HL 8 CRM Production	100.0	63.4±7.6	37.1±8.3	16.2±6.0	4.4±2.7	1.8±1.4

Mix Design Proportions:	HL 3 RUMAC	HL 8 RUMAC
HL 4 Stone (Hard Rock)	-	55.3%
HL 3 Stone (Hard Rock)	40.1%	-
Screenings (Hard Rock)	16.0%	11.7%
Asphalt Sand (TCG)	19.1%	13.0%
Washed Screenings (Hard Rock)	16.3%	-
Foundry Sand	-	12.2%
CRM (Recovery Technologies)	1.75%	1.75%
Asphalt Cement (Canadian 85/100)	6.7%	6.1%

Placement Conditions:

Weather: Low: 0°C   High: 13°C   Wind: 13 to 40 kph
Cloudy with rain and occasional snow flurries.

Paver: Cedarapids Greyhound CR461

Compaction Train: Smooth drum vibratory (1)
Static steel drum roller (2)
Water spray bars specified for all rollers.

[Grow-Rich]

TABLE B4-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	HL 3 RUMAC		OPSS 1150 HL 3 SPECIFICATIONS	HL 8 RUMAC		OPSS 1150 HL 8 SPECIFICATIONS
	JMF	Production		JMF	Production	
26.5 mm				100.0	100.0	100
19.0 mm				98.1	92.4-100.0	94-100
16.0 mm	100.0	100.0	100	89.0	84.6-95.6	77-95
13.2 mm	99.5	95.9-98.0	98-100	78.7	67.5-88.2	65-90
9.5 mm	79.5	78.6-84.4	75-90	62.3	41.2-72.7	48-78
4.75 mm	55.3	49.8-56.9	50-60	41.6	31.9-45.2	30-50
2.36 mm	40.8	37.2-41.4	36-60	31.4	26.0-36.5	21-50
1.18 mm	29.7	27.4-30.8	25-58	24.8	20.8-30.3	12-49
600 μm	19.7	18.8-21.9	16-45	19.8	12.0-24.4	6-38
300 μm	11.2	11.2-12.7	7-26	11.7	5.5-14.8	3-22
150 μm	5.6	5.7-6.7	3-10	5.0	3.9-7.0	1-9
75 μm	4.2	4.2-5.2	0-5	4.0	3.1-5.4	0-6
% AC	6.70	4.6-8.3	5.0-7.0	6.10	6.16-7.09	4.5-7.0
% CRM	1.75	-	NP	1.75	1.3-2.0	-
Stability, N	8250	8428	8900 mm	8500	8750	8000 mm
Flow, 0.25 mm	21.6	25.0	8 min	21.2	23.0	8 min
Air Voids, %	4.0	1.0	3 to 5	3.0	2.2	3 to 5
VMA, %	18.8	18.3	15.0 min	17.0	17.0	12.5 min
BRD, kg/m^3	2309	2358		2348	2341	
MRD, kg/m^3	2405			2418		
Recovered Pen		68	50 to 80			50 to 80

	Laydown Temperature	Thickness, mm	% Compaction
HL 3 RUMAC	150°C	73.9	94.4
HL 8 RUMAC	140°C-142°C	71.5	94.1

Placement Problems:

No traffic on mat until temperature less than 60°C. Plant breakdown (burner) resulted in five cold loads (HL 3 RUMAC). Granular base saturated with water.

[Grow-Rich]

PROJECT ENVIRONMENTAL DATA SHEET

Air Pollution Control Equipment: Cyclone and baghouse for aggregate drier, and baghouse for pugmill exhaust.

Air Emissions Type: Stack; combination of pugmill and rotary drier emissions 8 stack diameters downstream; 2 stack diameters upstream.

Plant Type: Batch Plant

Fuel: Natural Gas

Mix Type:	HL 3 RUMAC	HL 8 RUMAC
Discharge Temperature:	185°C	165°C
Drier Temperature:	NP	NP
Mixing Times	25s Dry 45s Wet	20s Dry 40s Wet

		HL 8			HL 8 RUMAC	
Test Dates (1992):	Oct 20	Oct 22	Oct 28	Nov 3	Nov 4	Nov 5
Production Rate, t/hr:	108	110	129	101	104	106

Air Program:

Compounds Sampled	Sampling Method
Inert Particulates Trace Metals Acid Gases	MOEE Method 5 sampling train with modified impingers as per CARB Method 436
Combustion Gases	Continuous emission monitoring by MOEE MAPS vehicle
Volatile Organic Compounds	Volatile Organic Sampling Train (VOST) USEPA Method 30
Polynuclear Aromatic Hydrocarbons Dioxins and Furans Chlorobiphenols Chlorophenols Chlorobenzenes	Modified MOEE Method 5 Sampling Train

Occupational Health Program: Not Applicable

Waste Program: Not Applicable

Ground and Surface Water Program: Not Applicable

PROJECT MONITORING DATA SHEET

Current Monitoring (JEGEL, September 1993)

Unable to inspect due to compost coverage. Site representative indicated that the pavement is performing well with no obvious surface distress.

B5. REGIONAL MUNICIPALITY OF HALDIMAND-NORFOLK #1

PROJECT TECHNICAL DATA SHEETS

Project: Regional Municipality of Haldimand-Norfolk #1

Date Completed: October 23 to November 15, 1990

Location: Regional Roads 9 and 55, 12.0 km

Agency: Regional Municipality of Haldimand-Norfolk

Consultants/Designers: Quentin Chapman/ORTECH/Haldimand-Norfolk

Contractor: Cayuga Materials & Construction Ltd.

Plant: Oil-fired batch with dry collector. CRM added via cold-feed conveyor.

Mix Types:	OPSS 1150 HL 3	HL 3 RUMAC	OPSS 1150 HL 8	HL 8 RUMAC
Tonnage Placed:		7048 t		6694 t

CRM Source: Rouse Rubber

Type: Ambient
No. 4 mesh

CRM Used: 317,880 kg (78,000 tire equivalents)

CRM Gradation	Percent Passing	
	CRM for HL 3 RUMAC Production	CRM for HL 8 RUMAC Production
9.5 mm	100.0	100.0
4.75 mm	98.9-100.0	98.8-99.9
2.36 mm	58.6-100.0	42.0-76.4
1.18 mm	33.0-95.0	28.0-61.7
600 μm	9.3-51.4	15.9-26.3
300 μm	0.8-16.1	2.7-10.7
150 μm	0.1-3.0	0.1-2.9
75 μm	0.1-0.5	0.1-0.5

Mix Design Proportions:

	HL 3	HL 3 RUMAC
HL 3 Stone (Cayuga)	39.7	44.9
Asphalt Sand (Cayuga)	41.1	29.0
Screenings (Cayuga)	13.7	19.6
CRM (Rouse Rubber)	-	2.0
Asphalt Cement (85/100)	5.5	6.5

	HL 8	HL 8 RUMAC
HL 8 Stone (Cayuga)	43.8	28.2
HL 3 Stone (Cayuga)	-	23.4
Asphalt Sand (Cayuga)	34.3	23.4
Screenings (Cayuga)	17.2	18.7
CRM (Rouse Rubber)	-	3.0
Asphalt Cement (85/100)	4.7	6.3

TABLE B5-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	HL 3		HL 3 RUMAC		OPSS 1150 HL 3	HL 8		HL 8 RUMAC		OPSS 1150 HL 8
	JMF	Production	JMF	Production		JMF	Production	JMF	Production	
26.5 mm						100.0	NP	100.0	100.0	100
19.0 mm				100.0		91.0	NP	97.5	95.5-100.0	94-100
16.0 mm	100.0	NP	100.0	99.6-100.0	100	83.0	NP	95.0	85.4-99.4	77-95
13.2 mm	99.6	NP	98.1	96.8-100.0	98-100	75.0	NP	90.0	80.7-98.5	
9.5 mm	84.7	NP	81.6	77.4-88.6	75-90	63.4	NP	70.8	61.6-80.3	48-78
4.75 mm	55.2	NP	50.0	44.3-55.1	45-65	50.0	NP	43.0	33.3-51.7	30-55
2.36 mm	48.3	NP	43.0	34.6-42.3	36-64	42.0	NP	36.5	25.9-38.7	21-54
1.18 mm	44.6	NP	37.7	29.1-35.3	25-58	38.0	NP	31.7	21.5-33.4	12-49
600 µm	36.3	NP	30.3	23.0-28.8	16-45	30.8	NP	31.7	17.1-27.1	6-38
300 µm	11.6	NP	11.8	9.6-13.1	7-26	10.3	NP	10.1	8.4-11.9	3-22
150 µm	4.7	NP	5.2	3.3-6.7	3-10	4.4	NP	4.7	2.8-5.3	1-9
75 µm	4.1	NP	4.0	2.2-5.5	0-5	3.9	NP	3.8	2.4-3.9	0-6
% AC	5.5	NP	6.5	5.80-6.61		4.7	NP	6.3	5.90-6.70	
% CRM	NA	NA	2.0	1.40-2.70	NA	NA	NA	3.0	2.5-3.1	NA
Stability, N	NP	NP	7599	7883-14688	6700 min	NP	NP	7470	8556-20080	5800 min
Flow, 0.25 mm	NP	NP	18.7	18.3-29.5	8 min	NP	NP	22.5	17.3-29.0	8 min
Air Voids, %	NP	NP	2.7	1.2-4.1	3 to 5	NP	NP	2.0	1.0-4.6	3 to 5 min
VMA, %	NP	NP	18.0	NP	14.5 min	NP	NP	17.9	NP	13.5 min
BRD, kg/m3	NP	NP	2320	2265-2344	NA	NP	NP	2320	2273-2303	NA
MRD, kg/m3	NP	NP	2384	2359-2414	NA	NP	NP	2374	2312-2399	NA
Recovered Pens				69-87	50-80				70-83	50-80

Placement Conditions:

Weather: Low -3°C High 22°C Mean 12°C

Paver: Unknown

Compaction Train:
- Static steel drum rollers (2)
- Rubber-tired roller (1)
- TSP wetting agent recommended to avoid pick-up

	Laydown Temperature	Thickness, mm	% Compaction
HL 3 RUMAC	120°C-157°C	31-69	90.7-99.1
HL 8 RUMAC	(140°C avg)	47-79	92.0-102.8

Placement Problems:

Occasional pick-up of mat by roller observed. Occasional free rubber (not fully mixed) observed.

[HN #1]

PROJECT ENVIRONMENTAL DATA SHEET

Air Pollution Control Equipment: Baghouse for aggregate drier, combustion gases and dust from mixing chamber.

Air Emissions Type: Stack sampling, exact sampling location unknown.

Plant Type: Stansteel TM 30 Batch Type Mixing Plant   Fuel: No. 2 Fuel Oil

Mix Type:	HL 3	HL 3 RUMAC		
Discharge Temperature:	130°C min-169°C max (149°C mean)			
Drier Temperature:	NP	NP		
Test Dates (1990):	Nov 15	Oct 26	Oct 27	Oct 29
Production Rate (t/hr):	134	196	121	196

Air Program:

Inert Particulates Trace Metals Acid Gases	MOEE Method 5 sampling train with modified impingers as per CARB Method 436
Combustion Gases	Continuous Emission Monitoring by MOEE MAPS vehicle
Volatile Organic Compounds	Volatile Organic Sampling Train (VOST), USEPA Method 30
Polynuclear Aromatic Hydrocarbons Dioxins and Furans Chlorobiphenyls Chlorophenols Chlorobenzenes	Modified MOEE Method 5 sampling train

Occupational Health Program: Not Applicable

Waste Program: Not Applicable

Ground and Surface Water Program: Not Applicable

PROJECT MONITORING DATA SHEETS

Date	Agency	Observations
1991	HN	A few centreline cracks and construction-related potholes.
1992	HN	A few centreline cracks and one transverse crack on Regional Road 9. Potholes have become worse since 1991.

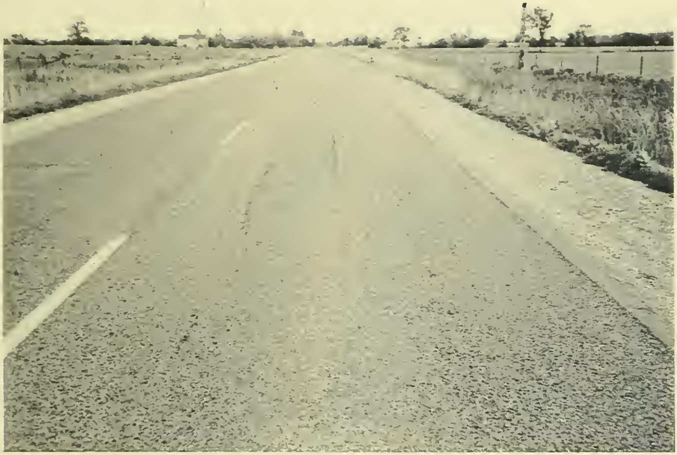
Current Monitoring (JEGEL, September 1993)

HL 3 RUMAC over HL 8 RUMAC

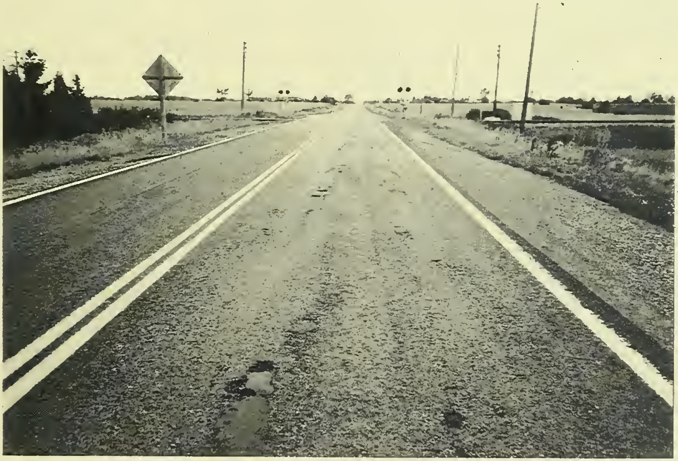
Section Limits	RR 9 RR 70 to RR 55	RR 55 RR 9 to Springvale	RR 55 Springvale to RR 20
Visual Rating	7.0	6.5	7.8
Ride Comfort Rating	6.0	5.0	7.0
General Condition:	Fair with localized poor areas. Construction joint cracking. Longitudinal cracking. Low to medium ravelling at ends of paving runs.	Fair to poor, medium to high severity ravelling requiring patching, extensive coarse aggregate pop-outs.	Fair with localized poor areas, low to medium severity ravelling, longitudinal and transverse cracking - part of polymelt bag observed in the mat.
General Comments:			Frequent heavy vehicle traffic to/from Springvale waste disposal facility.

Distress Density:

Distress Type	Severity	Length (Area) m (m^2)	Density %	Severity	Length (Area) m (m^2)	Density	Severity	Length (Area) m (m^2)	Density
Longitudinal cracking	L	25	0.1	L	1160	6.0	L	3220	20.8
Transverse cracking	L	38	0.2	L	126	0.7	L	21	0.2
Ravelling	L	(115)	0.5	L	(730)	3.8	L	185	1.2
	M	(15)	0.1	M	(250)	1.3			
				H	(130)	0.7			
Patching	L	(6)	<0.1						
Construction joint cracking	L	500	2.0				L	230	1.5



PHOTOGRAPH B5-1: Haldimand-Norfolk Regional Road 9 at Station 2+700 looking east. The HL 3 RUMAC surface course was placed in the late fall of 1990. Low severity longitudinal cracking is shown in the eastbound lane and along the centreline. Coarse aggregate and rubber particles have ravelled from the surface of the roadway.



PHOTOGRAPH B5-2: Haldimand-Norfolk Regional Road 55 at Station 0+200 looking north. The HL 3 RUMAC surface course was placed in the late fall of 1990. The surface of the pavement has deteriorated with many areas of medium to high severity ravelling and popouts evident. Localized patching has been necessary to maintain the surface of the pavement.

B6. REGIONAL MUNICIPALITY OF HALDIMAND-NORFOLK #2

PROJECT TECHNICAL DATA SHEETS

Project: Regional Municipality of Haldimand-Norfolk #2

Date Completed: August 10 to 31, 1992

Location: Regional Roads 9 and 55, 12.7 km

Agency: Regional Municipality of Haldimand-Norfolk

Consultants/Designers: JEGEL/ORTECH/Haldimand-Norfolk

Contractor: Cayuga Materials & Construction Ltd.

Plant: Oil-fired batch with dry collector. CRM added via cold-feed conveyor.

Mix Types:	OPSS 1150 HL 3	HL 3 RUMAC	OPSS 1150 HL 8	HL 8 RUMAC
Tonnage Placed:	241 t	6298 t	105 t	5153 t

CRM Source: Custom Cryogenic Recovery Technologies

Type: Cryogenic No. 10 mesh

CRM Used: (60,000 tire equivalents)

CRM Gradation	Percent Passing			
	Custom Cryogenic	Recovery Technologies	HL 8 CRM	HL 3 CRM
9.5 mm	100.0	100.0	100.0	100.0
4.75 mm	99.6	99.8	98.8-99.9	98.9-100.0
2.36 mm	49.9	26.0	42.0-76.4	58.6-100.0
1.18 mm	18.8	0.2	28.0-61.7	33.0-95.0
600 μm	6.0	0.2	15.9-26.3	9.3-51.4
300 μm	1.6	0.1	2.7-10.7	0.8-16.1
150 μm			0.1-2.9	0.1-3.0
75 μm	0.4	0.1	0.1-0.5	0.1-0.5

Mix Design Proportions:

	HL 3	HL 3 RUMAC	
		Custom Cryogenic CRM	Recovery Technologies CRM
HL 3 Stone (Cayuga)	36.5	36.1	36.1
Asphalt Sand (Cayuga)	29.1	27.7	27.7
Screenings (Cayuga)	29.1	27.7	27.7
CRM	-	2.0	2.0
Asphalt Cement (McAsphalt 85/100)	5.3	6.5	6.5

[HN #2]

	HL 8	HL 8 Custom Cryogenic CRM	HL 8 RUMAC Recovery Technologies CRM
19.0 mm Stone (Cayuga)	42.0	41.8	41.8
Asphalt Sand (Cayuga)	26.7	24.2	24.2
Screenings (Cayuga)	26.7	24.2	24.2
CRM	-	3.0	3.0
Asphalt Cement (McAsphalt 85/100)	4.6	6.8	6.5

Placement Conditions:

Weather: NP. Weather records indicate generally cloudy, warm weather

Paver: Unknown

Compaction Train: Static steel drum rollers (2)
Rubber-tired roller (1)
TSP wetting agent recommended to avoid pick-up

	Laydown Temperature	Thickness, mm	% Compaction
HL 3 RUMAC	130°C-135°C	NP	NP
HL 8 RUMAC			

Placement Problems:

Discharge temperature at start of job was 155°C. Plant was requested to lower this. No rubber tired roller use until mat temperature less than 60°C. Breakdown roller limited to 3 passes to prevent checking.

TABLE B6-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	HL 3		HL 3 RUMAC			OPSS 1150 HL 3	HL 8		HL 8 RUMAC			OPSS 1150 HL 8
	JMF	Production	JMF (CC)	JMF (RT)	Production		JMF	Production	JMF (CC)	JMF (RT)	Production	
26.5 mm							100.0	NP	100.0	100.0	100.0	100
19.0 mm							98.8	NP	98.9	98.9	93.2-98.7	94-100
16.0 mm					100.0	100	94.7	NP	93.1	93.1	82.2-95.1	77-95
13.2 mm	100.0	NP	100.0	100.0	99.5-100.0	98-100	88.4	NP	86.1	86.1	77.2-90.5	
9.5 mm	87.5	NP	81.8	81.8	83.2-87.9	75-90	69.5	NP	69.3	69.3	63.8-75.9	48-78
4.75 mm	55.0	NP	53.6	53.6	52.4-58.1	45-65	50.0	NP	47.6	47.6	45.1-53.4	30-55
2.36 mm	42.9	NP	42.3	42.3	40.4-45.0	36-64	39.0	NP	37.5	37.5	35.2-39.9	21-54
1.18 mm	35.9	NP	35.7	35.7	33.1-36.5	25-58	32.6	NP	31.7	31.7	28.6-32.8	12-49
600 um	27.6	NP	28.9	28.9	25.5-28.1	16-45	25.1	NP	25.7	25.7	22.4-26.1	6-38
300 um	10.0	NP	10.9	10.9	9.4-11.4	7-26	9.1	NP	9.8	9.8	9.0-11.2	3-22
150 um	4.5	NP	4.4	4.4	3.6-4.6	3-10	4.1	NP	4.0	4.0	3.5-4.9	1-9
75 um	3.9	NP	3.8	3.8	2.6-3.3	0-5	3.6	NP	3.5	3,5	2.4-3.7	0-6
% AC	5.3	NP	6.5	6.5	6.23-6.77	5.0-7.0	4.6	NP	6.5	6.8	6.30-6.65	4.5-7.0
% CRM	-	1	2.0	2.0	1.40-2.70	-	-		3.0	3.0	NP	-
Stability, N	9200	NP	2562	3315	7883-14688	6700 min	9011	NP	2917	2987	3053-4447	5800 min
Flow, 0.25 mm	9.3	NP	17.3	17.4	18.3-29.5	8 min	9.0	NP	19.9	24.6	18.0-25.7	8 min
Air Voids, %	4.6	NP	4.0	3.9	1.2-4.1	3 to 5	4.7	NP	3.5	4.1	3.9-6.4	3 to 5
VMA, %	15.8	NP	17.5	16.6	-	15 min	15.5	NP	16.9	18.0	-	14.0 min
BRD, kg/m^3	2374	NP	2270	2295	2265-2344		2383	NP	2264	2242	2207-2271	
MRD, kg/m^3	-	NP	2371	2389	2359-2414		-	NP	2346	2337	2342-2363	
Recovered Pen.		UN			UN			UN			UN	

[HN #2]

PROJECT ENVIRONMENTAL DATA SHEET

Air Pollution Control Equipment: Baghouse for aggregate drier, combustion gases and dust from mixing chamber.

Air Emissions Type: Stack sampling, non-ideal location, 7.9 stack diameters downstream, 1.4 stack diameters upstream.

Plant Type: Stansteel TM 30 Batch Type Mixing Plant Fuel: No. 2 Fuel Oil

Mix Type: HL 3 RUMAC

Discharge Temperature: 155°C
Drier Temperature: UN

Test Dates (1992):	Aug 10	Aug 11	Aug 12
Production Rate (t/hr):	110	133	120

Air Program:

Inert Particulates Trace Metals Acid Gases	MOEE Method 5 sampling train with modified impingers as per CARB Method 436.
Combustion Gases	Continuous Emission Monitoring by MOEE MAPS vehicle
Volatile Organic Compounds	Volatile Organic Sampling Train (VOST), USEPA Method 30.
Polynuclear Aromatic Hydrocarbons Dioxins and Furans Chlorobiphenyls Chlorophenols Chlorobenzenes	Modified MOEE Method 5 sampling train

Occupational Health Program: Not Applicable

Waste Program: Not Applicable

Ground and Surface Water Program: Not Applicable

PROJECT MONITORING DATA SHEET

Current Monitoring (JEGEL, September 1993)

Section Limits	RR 9 Villanova to RR 70	RR 9 Hall's Corner to Windham Centre	RR 9 Hall's Corner to Hwy 24	RR 55 RR 3 to Lake Erie
Visual Rating	9.5	9.5	9.5	9.8
Ride Comfort Rating	8.5	9.0	9.0	9.5
General Condition	Excellent No Distress	Very Good occasional pop-outs and low severity segregation at the end of a few paving runs.	Excellent occasional pop-outs No Distress	Excellent No Distress

PHOTOGRAPH

PHOTOGRAPH B6-1: Haldimand-Norfolk Regional Road 9 at Station 1+500 looking west. An HL 3 RUMAC mix was placed in 1992. The current condition of the pavement is excellent with no significant pavement distresses evident.

[MTO #1]

B7. MTO THAMESVILLE - PHASE I

PROJECT TECHNICAL DATA SHEETS

Project: MTO Thamesville - Phase I   Date Completed: October 2 to 16, 1990

Location: Highway 2, from east limit of Thamesville easterly for 13.5 km

Agency: MTO   Consultants/Designers: Trow/BAS/MTO

Contractor: Huron Construction   Plant: Oil-fired continuous drum mixer with wet collector. CRM metered into rear of drum with auger.

Mix Types: OPSS 1150 HL 4 Surface Course and HL 4 RUMAC

Tonnage Placed: HL 4 Surface: 5859 t   HL 4 RUMAC: 5717 t

CRM Source: National Rubber Company   Type: Ambient
No. 4 mesh

CRM Used: 127,000 kg (31,100 tire equivalents)

CRM Gradation	Percent Passing				
	4.75 mm	2.36 mm	1.18 mm	600 μm	300 μm
Specification	100.0	65±5	55±5	20±5	10±5
CRM	99.9	64.2	52.2	23.2	11.9
Production	98.2-99.9	47.4-74.7	39.2-60.1	18.9-33.1	7.6-15.4

Mix Design Proportions:

	OPSS 1150 HL 4 Surface	HL 4 RUMAC
HL 4 Stone (Bedrock Resources)	44.5	49.0
Asphalt Sand (Huron)	45.5	42.0
Blend Sand (Oxford)	10.0	7.0
CRM (National Rubber)	-	2.0
Asphalt Cement (McAsphalt 85/100)	5.3% of total mix	6.1% of total mix

Placement Conditions:

Weather:				
HL 4 Surface Course:	Low 8°C	High 26°C	Mean 17°C	Wind 14 kph
HL 4 RUMAC:	Low 7°C	High 16°C	Mean 11°C	Wind 9 kph

Paver: Cedarapids AT 619 Rubber tired paver

Compaction Train: Vibratory roller (1)   Rubber tired roller (1)
Static steel drum roller (2)

	Laydown Temperature	Thickness, mm	% Compaction
HL 4 Surface Course	140°C	49.9±3.6	95.4±1.2
HL 4 RUMAC	144°C	50.6±5.3	93.2±1.5

[MTO #1]

TABLE B7-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	HL 4 SURFACE COURSE		OPSS 1150 HL 4 SPECIFICATIONS	HL 4 RUMAC	
	JMF	PRODUCTION		JMF	PRODUCTION
19.0 mm	100.0		100	100.0	
16.0 mm	98.3		98-100	98.5	
13.2 mm	91.9		83-95	92.4	
9.5 mm	71.3		62-82	72.0	
4.75 mm	56.0		50-60	51.8	48.1-58.7
2.36 mm	47.2	56.0-64.5	27-60	43.1	
1.18 mm	38.6		16-60	34.8	
600 µm	30.0		8-47	26.6	
300 µm	18.3		4-27	15.8	
150 µm	7.5		1-10	7.0	
75 µm	3.4		0-6	3.2	2.4-4.3
% AC	5.30		5.0-7.0	6.10	5.89-6.29
% CRM	NA			2.0	1.6-2.1
Stability, N	10800	12655-16680	6700 min	5250	9427-12555
Flow, 0.25 mm	10.5	12.5-13.8	8 min	18.5	16.7-21.3
Air Voids, %	4.0	1.9-2.7	3 to 5	4.0	1.0-2.8
VMA, %	14.0	13.8-15.8	14.5 min	17.0	15.2-17.3
BRD, kg/m^3	2445	UN	NA	2337	UN
MRD, kg/m^3	2506	UN	NA	2418	UN
Recovered Pen		68	50-80	82	

Placement Problems:

Contract specified that pneumatic rubber tired roller was not to be used. However, cracking during breakdown rolling with static steel drum roller required use of rubber tired roller. This eliminated cracking but caused mat pickup.

Heat retention of HL 4 RUMAC was longer, and caused swelling of rubberized crack filler in original pavement.

[MTO #1]

PROJECT ENVIRONMENTAL DATA SHEET

Air Pollution Control Equipment: Venturi Scrubber, with cyclonic demister

Air Emissions Type: Stack sampling, 9.3 stack diameters downstream of exhaust fan for isokinetic sampling.

Plant Type: Boeing Model 200 Drum Mix Asphalt Plant Fuel: No. 2 Fuel Oil

Mix Type:	OPSS 1150 HL 4	HL 4 RUMAC
Discharge Temperature:	155°C	155°C
Drier Temperature:	132 to 171°C	121 to 165°C

Test Dates (1990):	Oct 2	Oct 3	Oct 4	Oct 5	Oct 11	Oct 15	Oct 16
Production Rate (t/hr):	142.3	156.6	143.2	162.8	140.6	147.6	148.7

Air Program: Not Applicable

Occupational Health Program:

Compounds Sampled	Sampling Protocol
Particulates	NIOSH 0500
Heavy Metals	OSHA Method 192
Coal Tar Pitch Volatiles	NIOSH 1501
Polynuclear Aromatic Hydrocarbons	NIOSH 5506

Waste Program:

Materials Sampled	Criteria
HL 4 Surface Course Hot Mix	O.Reg 309 (now O.Reg 347)
HL 4 RUMAC Hot Mix	
CRM	
Scrubber Waste Water Sludge	
Scrubber Waste Water	Toronto Model Sewer-Use By-law

Ground and Surface Water Program:

Waters Sampled	Criteria
Scrubber Waste Water	Ontario Provincial Water Quality Objectives (July 1991)
Lagoon Water	CCME Interim Canadian Quality Criteria for Contaminated Sites (September 1991)

PROJECT MONITORING DATA SHEETS

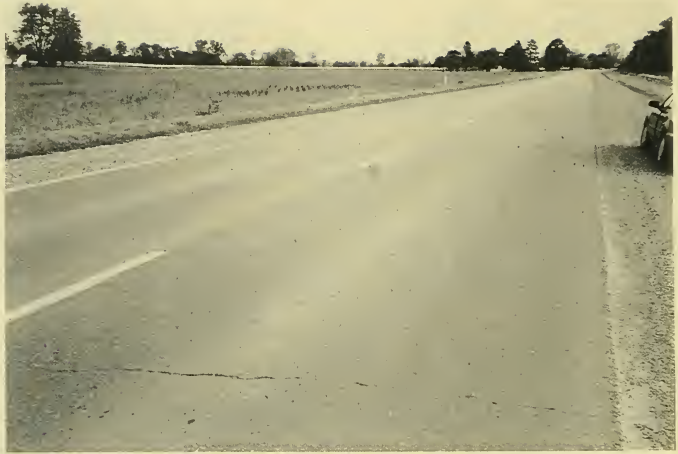
Date	Agency	Observations
Feb/March 1991	Trow	Reflection cracking from concrete base in both mix types. Pitting observed in HL 4 RUMAC and breakdown of pavement edges.
1991	MTO	Large aggregate particles being dislodged from HL 4 RUMAC. Centreline construction joint opening up and ravelling in HL 4 RUMAC. HL 4 RUMAC mat is more permeable and takes longer to dry.
1992	MTO	No apparent change in popouts from previous inspection. 71 percent of original cracks reflected through HL 4 Surface Course. 73 percent of original cracks reflected through HL 4 RUMAC.

Current Monitoring (JEGEL, September 1993)

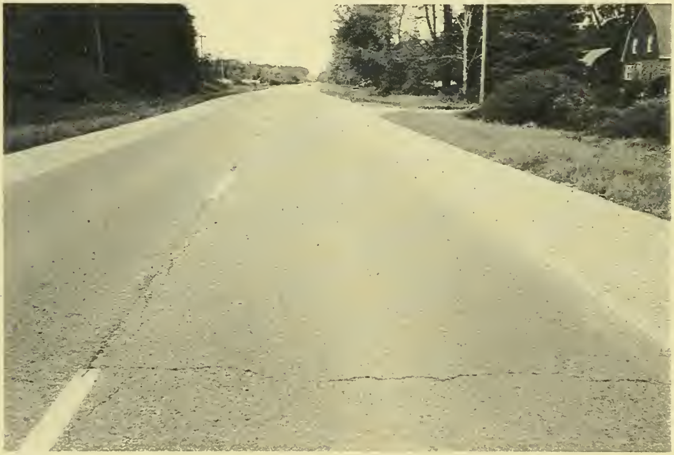
	OPSS HL 4 Surface Course	HL 4 RUMAC
Station	3+230 to 6+000	19+600 to 21+850
Visual Rating	8.4	7.5
Ride Comfort Rating	8.0	8.0
General Condition	Fair to good Low severity transverse cracking and centreline joint cracking.	Fair to good Low severity transverse cracking; localized low severity ravelling and coarse aggregate pop-outs; CRM coarse aggregate particles readily observed.
General Comments:	Many transverse cracks do not extend across the full width of the pavement. Many of the transverse cracks start at the middle of the lane and extend to the shoulder and centreline.	Ravelling and pop-outs most evident at end of paving loads and transition to conventional mix. Low severity ravelling observed at high severity transverse cracks.

Distress Density:

Distress Type	Severity	Length (Area) m (m^2)	Density %	Severity	Length (Area) m (m^2)	Density %
Longitudinal cracking	L	25	0.1	L	45	0.3
Transverse cracking	L	2725	13.1	L	3100	18.4
Ravelling	L	(15)	0.1	L	(75)	0.4
Construction joint cracking	L	642	3.1	L	3500	70.7



PHOTOGRAPH B7-1: Thamesville Phase I at Station 4+700 looking west. This conventional HL 4 surface mix was placed in the fall of 1990. Low to medium severity transverse cracks are present at 7 to 8 m intervals.



PHOTOGRAPH B7-2: Thamesville Phase I at Station 20+100 looking east. This HL 4 RUMAC surface mix was placed in the fall of 1990. Note the medium severity transverse crack in the foreground and the longitudinal construction joint crack along the centre of the roadway. Some low severity ravelling and coarse aggregate popouts are also shown.

[MTO #2]

B8. MTO THAMESVILLE - PHASE II

PROJECT TECHNICAL DATA SHEETS

Project: MTO Thamesville - Phase II   Date Completed: October 9 to 23, 1991

Location: Highway 2 near Thamesville, 23.8 km

Agency: MTO   Consultants/Designers: Trow/BAS/MTO

Contractor: Huron Construction   Plant: Oil-fired continuous drum mixer with wet collector. CRM metered into rear of drum with auger.

Mix Types:	RHM (30/70)	RHM (30/70) RUMAC	HL 4 RUMAC	HL 4
Tonnage Placed:	3680 t	3517 t	2789 t	947 t

CRM Source: National Rubber Company   Type: Ambient
No. 10 mesh

CRM Used: 108,000 kg (26,500 tire equivalents)

CRM Gradation: Percent Passing

	2.36 mm	1.18 mm	600 μm	300 μm	150 μm	75 μm
Specification	95-100	70-80	30-40	10-20		2-10
CRM	UN	UN	UN	UN		UN
Production	100.0	60.5±4.1	34.2±2.2	14.7±1.5		1.7±0.6

Mix Design Proportions:

	HL 4	HL 4 RUMAC	RHM (30/70)	RHM (30/70) RUMAC
HL 4 Stone (Bedrock Resources)	39.9	50.0	34.5	36.5
Asphalt Sand (Huron)	45.6	33.0	35.5	33.5
Blend Sand (Komoka)	9.5	15.0	-	-
RAP (90-800)	-	-	30.0	30.0
CRM	-	2.0	-	1.2
Asphalt Cement (McAsphalt 85/100)	5.0	6.2	NA	NA
(McAsphalt 150/200)	NA	NA	5.0	5.5

Placement Conditions:
Weather: Low 8°C   High 17°C   Mean UN

Paver: Cedarapids Greyhound CR S61 Rubber Tired Paver
Compaction Train: Vibratory roller (1)   Rubber-tired roller (1)
Static steel drum roller (1)

	Laydown Temperature	Thickness, mm	% Compaction
HL 4	120°C	UN	
HL 4 RUMAC	130°C-145°C	UN	92.1
RHM (30/70)	120°C	UN	94.7
RHM (30/70) RUMAC	130°C-145°C	UN	91.2

Placement Problems:
Compaction problems similar to MTO Thamesville - Phase 1. Mixes prone to checking, limiting steel drum roller to a few passes. Severe pick-up by rubber-tired roller required that mat be allowed to cool about 60°C. Segregation and open texture was observed until contractor changed pavers.

TABLE B8-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	HL 4 Surface		HL 4 RUMAC		OPSS 1150 HL 4 SPECIFICATION	RHM (30/70)		RHM (30/70) RUMAC	
	JMF	Production	JMF	Production		JMF	Production	JMF	Production
19.0 mm		100.0	100.0	100.0	100	100.0	100.0	100.0	100.0
16.0 mm	100.0	99.3	99.0	98.4	98-100	98.9	98.6	99.2	99.3
13.2 mm	92.7	87.6	90.0	91.2	83-95	90.0	93.4	91.6	92.7
9.5 mm	71.6	66.1	69.1	71.4	62-82	72.1	76.2	72.1	73.2
4.75 mm	57.1	54.8	52.1	53.1	50-60	55.0	57.0	53.1	53.7
2.36 mm	46.9	44.8	45.2	45.1	27-60	47.8	48.5	45.4	45.3
1.18 mm	37.1	34.2	37.6	37.1	16-60	40.8	41.2	39.3	38.0
600 μm	25.8	24.4	27.2	28.0	8-47	32.4	32.2	30.1	29.5
300 μm	13.1	13.9	15.1	15.9	4-27	19.7	20.2	18.1	17.5
150 μm	5.1	5.5	5.2	5.2	1-10	6.5	7.9	7.2	6.1
75 μm	2.3	2.9	3.0	2.4	0-6	3.1	4.5	4.2	3.1
% AC	5.0	4.95	6.20	6.44	5.0-7.0	5.0	5.09	5.50	5.80
% CRM	NA	NA	2.00	2.26		NA	NA	2.00	2.57
Stability, N	8300	13018	5800	9266	6700 min	10500	14088	6725	12523
Flow, 0.25 mm	8.3	11.6	12.0	14.9	8 min	7.1	11.7	12.5	13.4
Air Voids, %	3.4	1.9	4.0	3.3	3 to 5	4.0	2.2	3.0	2.7
VMA, %	15.0	13.7	18.7	18.4	14.5 min	14.2	13.1	16.5	16.2
BRD, kg/m^3	2410	UN	2320	UN	NA	2415	UN	2365	UN
MRD, kg/m^3	UN	UN	2420	UN	NA	2513	UN	2438	UN
Recovered Pen	NA	67	NA	66	50-80	NA	UN	72	UN

PROJECT ENVIRONMENTAL DATA SHEETS

Air Pollution Control Equipment: Venturi Scrubber, with cyclonic demister

Air Emissions Type: Stack sampling, 9.3 stack diameters downstream of exhaust fan for isokinetic sampling.

Plant Type: Boeing Model 200 Drum Mix Asphalt Plant Fuel: No. 2 Fuel Oil

Mix Type: RHM (30/70), RHM (30/70) RUMAC, HL 4 RUMAC, HL 4

		RHM (30/70)			RHM (30/70) RUMAC				HL 4 RUMAC	
Discharge Temp.:	140°C	140°C	150°C	160°C	160°C	160°C	150°C	155°C	150°C	150°C
Drier Temp.:	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
					October					
Test Dates (1991)	9	10	11	15	16	17	18	21	22	23
Production Rate, t/hr	140.6	130.8	131.1	124.3	134.5	127.0	153.2	132.4	130.4	119.4

Air Program:

Compounds Sampled	Sampling Methods
Inert Particulates Trace Metals Acid Gases	MOEE Method 5 sampling train with modified impingers as per CARB Method 436
Combustion Gases	Continuous emission monitoring by MOEE MAPS vehicle
Volatile Organic Compounds	Volatile Organic Sampling Train (VOST) USEPA Method 30
Polynuclear Aromatic Hydrocarbons Dioxins and Furans Chlorobiphenols Chlorophenols Chlorobenzenes	Modified MOEE Method 5 Sampling Train

Occupational Health Program:

Compounds Sampled	Sampling Protocol
Particulates	NIOSH 0500
Heavy Metals	OSHA Method 192
Coal Tar Pitch Volatiles	NIOSH 1501
Polynuclear Aromatic Hydrocarbons	NIOSH 5506

Waste Program:

Materials Sampled	Criteria
HL 4 Surface Course Hot Mix HL 4 RUMAC Hot Mix CRM Scrubber Waste Water Sludge	O.Reg 309 (now O.Reg 347)
Scrubber Waste Water	Toronto Model Sewer-Use By-law

Ground and Surface Water Program:

Waters Sampled	Criteria
Scrubber Waste Water	Ontario Provincial Water Quality Objectives (July 1991)
Lagoon Water	CCME Interim Canadian Quality Criteria for Contaminated Sites (September 1991)

[MTO #2]

PROJECT MONITORING DATA SHEET

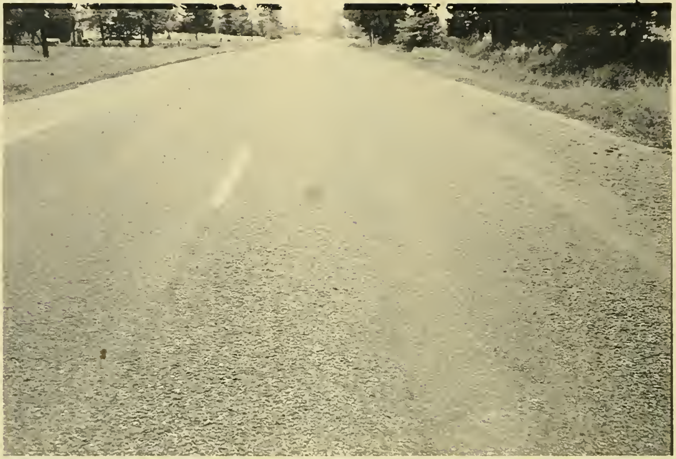
Date	Agency	Observations
July 1992	MTO	63% of original cracks reflected through RHM (30/70) 67% of original cracks reflected through RHM (30/70) RUMAC. Construction joint crack at centreline completely open through RHM (30/70) RUMAC section. HL 4 RUMAC and RHM (30/70) RUMAC sections both exhibit coarse aggregate loss. HL 4 RUMAC using #10 mesh rubber performing better than HL 4 RUMAC using #4 mesh rubber (MTO Thamesville I).

Current Monitoring (JEGEL, September 1993)

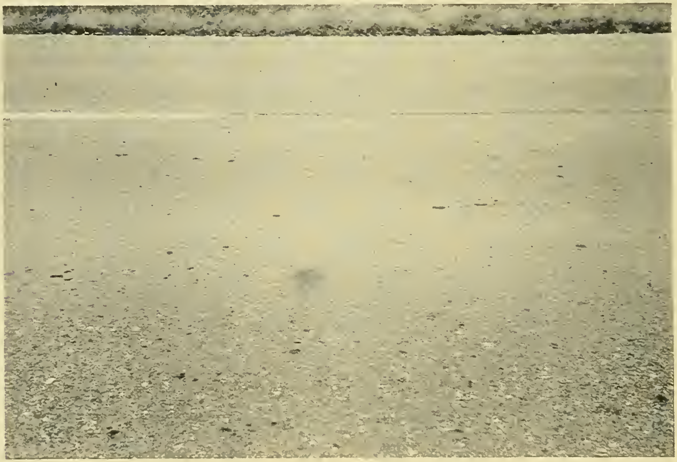
Mix Type: Station:	RHM (30/70) RUMAC 0+000 to 2+500	RHM (30/70) 2+500 to 3+500	HL 4 3+500 to 5+750	HL 4 RUMAC 5+750 to 7+850
Visual Rating	8.0	9.0	9.0	8.5
Ride Comfort Rating	9.0	9.5	9.5	9.0
General Condition	Very good Occasional low transverse cracks, construction joint cracking.	Very good Rusty brown pop-outs (ironstone natural aggregates). Occasional low transverse cracks, construction joint cracking.	Excellent Low transverse cracks, low longitudinal cracks, construction joint cracks.	Good to very good Frequent low transverse cracks, coarse aggregate pop-outs, segregation at ends of paving runs.
General Comments	Coarse mix texture with dull appearance.	Ironstone(?) not durable.	Occasional ironstone(?) particles.	Coarse mix texture with dull appearance.

Distress Density:

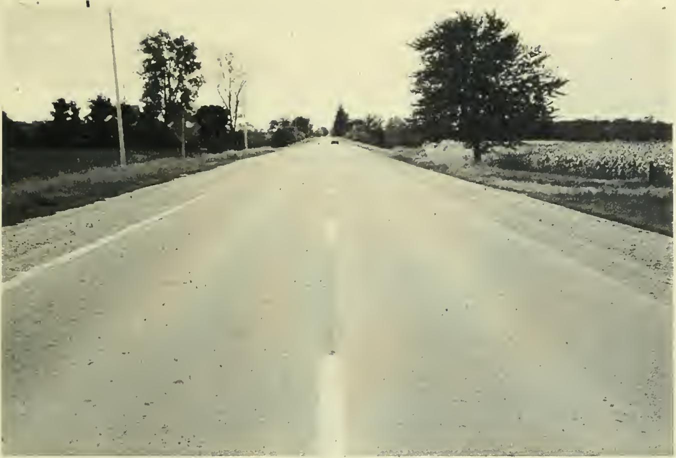
Distress Type	Severity	Length (Area)	Density	Severity	Length (Area)	Density	Severity	Length (Area)	Density	Severity	Length (Area)	Density
Longitudinal cracking	L	14	0.1				L	4	<0.1	L	19	0.1
Transverse cracking	L	870	4.6	L	195	2.6	L	870	5.2	L	760	4.8
Construction joint cracking	L	700	3.7	L	800	10.7	L	325	1.9	L	150	1.0



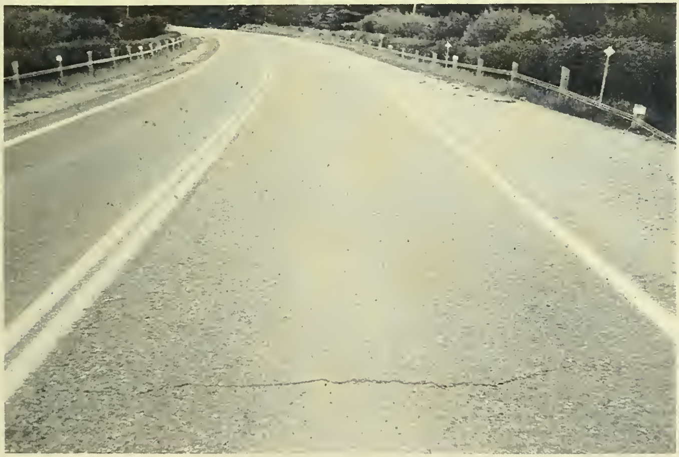
PHOTOGRAPH B8-1: Thamesville Phase II at Station 2+500 looking west. This RHM (30/70) RUMAC mix was placed in the fall of 1991. The surface course mix has a dull appearance. Localized ravelling is shown in the foreground.



PHOTOGRAPH B8-2: Thamesville Phase II at Station 3+000. The condition of this RHM (30/70) mix is considered to be very good. The brown rusty spots on the surface are likely the result of the use of non-durable ironstone natural aggregates in the mix.



PHOTOGRAPH B8-3: Thamesville Phase II at Station 4+950 looking east. The condition of this conventional HL 4 mix is considered to be excellent. Low severity cracking is evident transverse to the roadway and along the centreline.



PHOTOGRAPH B8-4: Thamesville Phase II at Station 5+775 looking east. The condition of the HL 4 RUMAC mix is considered to be good. The cracking in this section of pavement was low to medium in severity and somewhat more random in nature than the other trial sections. Note the somewhat coarse surface texture.

B9. MTO HIGHWAY 400

PROJECT TECHNICAL DATA SHEETS

Project: MTO Highway 400 Date Completed: July 24, 1990

Location: MTO Contract 90-07, Highway 400 south of Barrie

Agency: MTO Consultants/Designers: MTO/Rouse Rubber Industries

Contractor: Allan G. Cook Construction Co. Limited

Plant: Gas fired continuous drum mixer with dry collector

Mix Types:	HL 1 AR	HL 4 AR
Tonnage Placed:	UN	UN

CRM Source: Rouse Rubber Industries Inc. Type: Ambient (Ultrafine)
No. 80 mesh

CRM Gradation: NP

Mix Design Proportions:

	HL 1	HL 1 AR
HL 1 Stone (3M)	50.0	50.0
Asphalt Sand (A.G. Cook)	37.5	37.5
Screenings (A.G. Cook)	12.5	12.5
% Asphalt Cement (Petrocan 85/100)	5.0	5.0 (7.0% AR)

	HL 4	HL 4 AR
HL 4 Stone (A.G. Cook)	44.0	44.0
Asphalt Sand (A.G. Cook)	56.0	56.0
% Asphalt Cement (Petrocan 85/100)	5.9	5.9 (7.0% AR)

Placement Conditions:

Weather: Low 23°C High 28°C

Paver: Barber Greene BG245

Compaction Train: Vibratory roller (1)
Rubber tired roller (1)

	Laydown Temperature	Thickness, mm	% Compaction
HL 1 AR	130°C	34,48	96.5
HL 4 AR	130°C	55,60	99.1

TABLE B9-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	HL 1 AR		OPSS 1150 HL 1 SPECIFICATIONS	HL 4 AR		OPSS 1150 HL 4 SPECIFICATIONS
	JMF	Production		JMF	Production	
19.0 mm						100
16.0 mm	100.0		100	100.0		98-100
13.2 mm	99.7		98-100	93.8		85-95
9.5 mm	79.2		75-90	77.3		62-82
4.75 mm	47.6	47.3	45-65	55.0	58.5	40-67
2.36 mm	42.5		36-64	50.1		27-66
1.18 mm	38.2		25-58	45.1		16-60
600 μm	30.1		16-45	35.6		8-47
300 μm	13.3		7-26	15.9		4-27
150 μm	2.5		3-10	3.3		1-10
75 μm	0.6	2.9	0-5	1.1	2.0	0-6
% AC	5.0	4.82	5.0-7.0	5.9	5.14	5.0-7.0
% AR	7.0	-	NA	7.0	-	NA
Stability, N	9340	12985	8900 mm	7560	7776	8000 mm
Flow, 0.25 mm	8.8	12.6	8 min	9.0	10.3	8 min
Air Voids, %	3.5	3.6	3 to 5	2.5	6.3	3 to 5
VMA, %	15.1	14.6	16.4	14.5	17.8	15.0
BRD, kg/m^3	2504	2524	NA	2383	2319	NA
MRD, kg/m^3	2573	2618	NA	2444	2476	NA
Recovered Pen	UN	UN		UN	UN	

Placement Problems: None reported.

PROJECT ENVIRONMENTAL DATA

No environmental monitoring or testing completed.

PROJECT MONITORING DATA SHEET

Current Monitoring (JEGEL, September 1993)

	HL 1 CONTROL	HL 1 AR
Station	17+040 to 17+400	15+010 to 15+335
Visual Rating	9.0	9.0
Ride Comfort Rating	9.0	9.0
General Condition	Excellent occasional low transverse cracking	Excellent occasional low transverse cracking
General Comments		HL 1 AR pavement has about 50% less transverse cracking than control section.

Distress Density:

Distress Type	Severity	Length (Area) m (m^2)	Density %	Severity m (m^2)	Length (Area) %	Density
Transverse Cracking	low	25	7.0	low	45	3.7

PHOTOGRAPH

PHOTOGRAPH B9-1: Highway 400 Southbound test section looking south. The HL 1 AR section was placed in the summer of 1990. The condition of this test section is considered to be excellent with 50% less transverse cracking that the conventional HL 1 control section.

[Lambton CIP]

B10. COUNTY OF LAMBTON

PROJECT TECHNICAL DATA SHEETS

Project: County of Lambton
Cold In-Place Recycling

Date Completed: July 27 to 30, 1992

Location: Lambton County Road 33, north of Lasalle Road, 12 km.

Agency: County of Lambton

Consultants/Designers: Trow/County of Lambton

Contractor: MSO Construction

Plant: Cold In-Place Recycling Train.

Mix Types: Cold In-Place Recycled Mix with 3.0 CRM
HL 3 Overlay

CRM Source: Recovery Technologies Type: Cryogenic

CRM Used: 64,300 kg (16,000 tire equivalents)

CRM Gradation: Percent Passing

9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 μm	300 μm	150 μm	75 μm
100.0	97.4	34.5	0.5	0.5	0.4	0.3	0.1

Mix Design Proportions: Oregon DOT Design Procedure

HL 4 Stone (NP)	18.0
RAP (C.R. 33)	82.0
CRM (Recovery Technologies)	3.0
Emulsion (HF-150)	1.7

JMF and Production Test Results:

Mix Gradation Not Provided

Stability, N at 60°C	4500
at 25°C	1778 [?]
Flow, 0.25 mm	26.2
Air Voids, %	7.0
VMA, %	NP
BRD, kg/m^3	2200
MRD, kg/m^3	2355
Recovered Pen	32

Placement Conditions:
Weather: Rain on 3 of 4 paving days; high humidity (59 to 100%).
Average temperature: 14.4°C (cooler than normal).

Paver: MSO Cold In-Place Recycling Train

Compaction Train: Static Steel Drum Roller (1)
Rubber-tired Roller (1)

% Compaction: 96.2
Thickness: NP (75 mm depth specified)

Placement Problems:

Extensive ravelling and rutting observed on first day when exposed to traffic. The entire area was remilled and remixed with addition of 2.1% HF-150 emulsion, and only localized rutting and ravelling occurred.

Hot mix surface course (overlay) applied after about 3½ weeks - HL 4 surface course thickness increased from 40 mm specified to 60 mm.

PROJECT ENVIRONMENTAL DATA:
Not Applicable

PROJECT MONITORING DATA SHEET

Current Monitoring: (JEGEL, September 1993)

Section: County Road 33, from 125 m north of Lasalle Road to 3000 m north.

	HL 3 over Cold In-Place with 3.0% CRM
Visual Rating	9.5
Ride Comfort Rating	9.0
General Condition	Excellent no distress evident

General Comments: Several transverse reflection cracks noting at the start and end of the test and control sections in areas where underlying pavement were not cold in-place recycled. Existing pavement consisted of 75 to 100 mm of badly cracked hot-mix asphalt over concrete base.

PHOTOGRAPH

PHOTOGRAPH B10-1: Lambton County Road 33 approximately 2100 m north of LaSalle Road looking north. Cold in-place recycling technology was used in this section in the summer of 1992. The condition of the conventional HL 3 surface course mix is excellent with no pavement surface distresses evident.

B11. HALTON WASTE MANAGEMENT SITE

PROJECT TECHNICAL DATA SHEETS

Project: Halton Waste Management Site

Date Completed: August 25 to September 16, 1992

Location: Britannia Road and Fifth Line, Milton

Agency: Region of Halton

Consultants/Designers: Quentin Chapman/Halton

Contractor: Warren Bitulithic Ltd.

Plant: Gas-fired Boeing Model 200 batch with dry collector. CRM added by cold feed/RAP conveyor to batch weigh hopper.

Mix Types: HL 3 RUMAC and HL 8 RUMAC

Tonnage Placed: HL 3 RUMAC: 3600 t HL 8 RUMAC: 6400 t

CRM Source: Scopcat Co. Canada

Type: Ambient
No. 10 mesh

CRM Used: 149,360 kg (37,000 tire equivalents)

CRM Gradation: NP

Mix Design Proportions:

	HL 3 RUMAC	HL 8 RUMAC
HL 4 Stone (TCG)	41.0%	-
HL 8 Stone (TCG)	-	52.2%
Asphalt Sand (TCG)	40.4%	25.9%
Washed Screenings (TCG)	11.3%	14.8%
CRM (Scopcat)	1.30%	1.50%
Asphalt Cement (Canadian 85/100)	6.00%	5.60%

Placement Conditions:
Weather: Sunny, with occasional heavy rain.
Daily temperatures: Low: 11°C High: 25°C

Paver: Cedarapids Greyhound CR461

Compaction Train:	
Vibratory steel drum roller	(1)
Rubber tired roller	(1)
Static steel drum roller	(1)

Wetting agent such as TSP recommended.

	Laydown Temperature	Thickness, mm	% Compaction
HL 3 RUMAC	140°C-170°C	45 mm specified	NP
HL 8 RUMAC	115°C-158°C	65 mm specified	NP

[Halton]

TABLE 11-1 JMF AND PRODUCTION TEST RESULTS - PERCENT PASSING

SIEVE SIZE	HL 3 JMF	HL 3 RUMAC		OPSS 1150 HL 3 SPECIFICATION	HL 8 JMF	HL 8 RUMAC		OPSS 1150 HL 8 SPECIFICATION
		JMF	Production			JMF	Production	
26.5 mm					NP	100.0	100.0	100
19.0 mm					NP	94.4	93.2-100.0	94-100
16.0 mm	NP	100.0	100.0	100	NP	82.2	77.5-90.3	77-95
13.2 mm	NP	99.7	98.3-100.0	98-100	NP	75.0	68.4-81.4	65-90
9.5 mm	NP	81.4	77.3-90.9	75-90	NP	59.3	49.1-68.6	48-78
4.75 mm	NP	55.0	48.9-62.0	50-60	NP	43.1	37.2-48.9	30-50
2.36 mm	NP	40.7	33.7-51.6	36-60	NP	34.5	29.4-42.1	21-50
1.18 mm	NP	30.5	23.2-40.7	25-58	NP	28.2	22.0-36.7	12-49
600 µm	NP	19.6	16.3-26.8	16-45	NP	19.5	15.5-27.2	6-38
300 µm	NP	10.7	7.8-15.0	7-26	NP	8.8	8.2-12.9	3-22
150 µm	NP	5.6	3.3-11.1	3-10	NP	4.2	3.6-8.6	1-9
75 µm	NP	3.8	1.9-7.2	0-5	NP	3.0	1.7-6.4	0-6
% AC	NP	6.00	5.60-6.48	5.0-7.0	NP	5.60	4.80-6.13	4.5-7.0
% CRM	NP	1.30	0.1-13.0?	NA	NP	1.50	1.2-2.1	NA
Stability, N	NP	8200	9500-10660	6700 min	NP	10200	10125	5800 min
Flow, 0.25 mm	NP	14.1	12.0-19.1	8 min	NP	15.9	16.1	8 min
Air Voids, %	NP	4.0	0.3-2.6	3 to 5	NP	4.0	2.0	3 to 5
VMA, %	NP	17.2	-	15.0 min	NP	16.8	16.3	13.5 min
BRD, kg/m^3	NP	2376	2363-2428		NP	2371	2403	
MRD, kg/m^3	NP	2478	2425-2471		NP	2470	2453	
Recovered Pen	NP		NP		NP		NP	

Placement Problems:

Hairline cracking at edges due to unstable granular base. Occasional high variation in CRM addition levels (0.1 to 2.0%). Occasional wide variations in mix gradation.

PROJECT ENVIRONMENTAL DATA:

No environmental monitoring or testing completed.

PROJECT MONITORING DATA SHEET

Current Monitoring: (JEGEL, September 1993)

HL 3 RUMAC over HL 8 RUMAC

Location: All internal roadways

Visual Rating: 9.5
Ride Comfort Rating: 9.5

General Condition: Excellent
- some low severity construction joint cracking. Two patches were observed at approaches to speed bumps where surface course tearing/slippage occurred due to high truck braking forces. Used mainly by heavy trucks.

General Comments: - most areas have received little heavy truck traffic to date.

Distress Density:

Distress Type	Severity	Length (Area) m (m^2)	Density %
Construction joint cracking	L	120	0.7

PHOTOGRAPH

PHOTOGRAPH B11-1: Halton Waste Management Facility Road 2. The condition of this HL 3 RUMAC mix is considered to be excellent after one year of service.

B12. TOWNSHIP OF PROTON ROAD 22

PROJECT TECHNICAL DATA SHEETS

Project: Township of Proton Road 22 Date Completed: May 27 to 29, 1992

Location: Grey County, 4.6 km

Agency: Township of Proton Consultants/Designers: TAK

Contractor: The Murray Group Plant: Batch

Mix Types:	
HL 4 1.0% RUMAC (85/100)	805 t
HL 4 1.5% RUMAC (85/100)	575 t
HL 4 1.5% RUMAC (150/200)	1130 t

CRM Source: Baker Rubber Type: Ambient
No. 10 Mesh (from Grey #1)

CRM Used: 28570 kg (7,000 tire equivalents)

CRM Gradation - NP

Mix Design Proportions:

	HL 4 1.0% RUMAC	HL 4 1.5% RUMAC	HL 4 1.5% RUMAC
HL 4 Stone (Murray)	44.5	44.5	44.5
Asphalt Sand (Cayuga)	41.3	41.0	41.0
Screenings (Cayuga)	13.2	13.0	13.0
CRM (Baker)	1.0	1.5	1.5
Asphalt Cement (McAsphalt)	6.3 (85/100)	6.8 (85/100)	6.7 (150/200)

Placement Conditions:
Weather: Sunny, 12 to 15°C

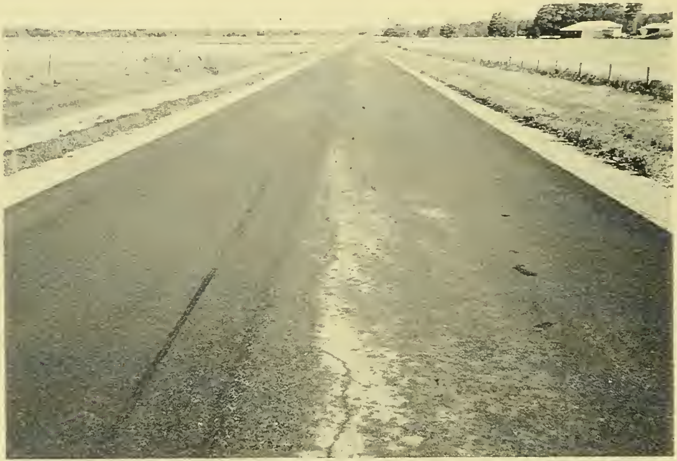
Paver: Cedarapids
Compaction Train: Static steel drum roller (2)
Rubber tired roller (1)

	Laydown Temperature	Thickness, mm	% Compaction
All mixes	152°C-168°C	NP	96.5

Placement Problems:
Some roller pick-up and segregation.

PROJECT ENVIRONMENTAL DATA:
No environmental monitoring or testing completed.

PHOTOGRAPH B12-1: Proton Township Road 22 approximately 2800 m north of Proton Road 10 looking north. This HL 4 1.0% RUMAC (85/100) mix was placed in the spring of 1992. Although the current surface condition of the roadway is excellent, the relatively thin RUMAC overlay was placed over pavement suffering from high severity load related distress such as alligator cracking.



PHOTOGRAPH B12-2: Proton Township Road 22 approximately 3300 m north of Proton Road 10 looking north. This HL 4 1.5% RUMAC (85/100) mix was placed in the spring of 1992. Several low to medium severity longitudinal cracks were observed around the middle of the pavement.

APPENDIX C

ASPHALT TECHNOLOGY

C1. GENERAL

Ontario Provincial Standard Specifications (OPSS)* for construction and materials, supplemented by other standards (American Society for Testing and Materials (ASTM), Canadian Standards Association (CSA), Canadian General Standards Board (CGSB), etc.) and special provisions based on local experience, are widely adopted for asphalt technology and pavement construction. There are currently only a few Ontario asphalt technology specifications** that directly deal with crumb rubber modifier (CRM) use***. These are:

OPSS 1212	Hot-Poured Rubberized Asphalt Joint Sealing Compound;
OPSS 1213	Hot Applied Rubberized Asphalt Water-proofing Membrane; and
OPSS 1214	Hot Applied Rubberized Mastic Water-proofing Membrane.

Much of the asphalt technology information presented here is based on applied Ontario experience and the Ministry of Transportation (MTO) "Pavement Design and Rehabilitation Manual", which JEGEL was involved with during its preparation and presentations. Emphasis is placed on flexible (asphalt) pavements as they make up the greatest part of the Ontario road/highway network and were used for the Ontario rubber modified asphalt demonstration projects.

It should be noted that there are currently no standard Ontario (OPSS, MTO or municipal) mix design procedures, materials specifications or construction specifications for crumb rubber modifier (CRM) use in rubber modified asphalt pavement (RUMAC), recycled rubber modified asphalt pavement (RRUMAC), rubber modified cold in-place recycling (RUMCIP) or rubber modified asphalt cement (AR). For general guidance, an example draft special provision for RUMAC is given in Appendix D, noting that the use of this example draft special provision is subject to: the specifier selecting the appropriate CRM addition rate, type and grading (size), etc.; and an overall user agency understanding of the technical status of RUMAC use and its potential performance. A general guide work plan for the evaluation of major demonstration CRM paving projects is given in Appendix E. Appendices D and E, particularly, are based on the FHWA "State of the Practice - Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier", which provides fairly comprehensive RUMAC and AR design and specification guidance, particularly at this early stage of generic dry process RUMAC development.

C2. PAVEMENTS

C2.1 General

Typical pavement structures (Figure C1) are made up of layers of granular subbase, granular base and surfacing, designed to support the traffic loadings (magnitude and replications) for the site subgrade and environmental conditions.

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* See Appendix G for abbreviations.

** See Sections C7. of this Appendix for typical Ontario specification references.

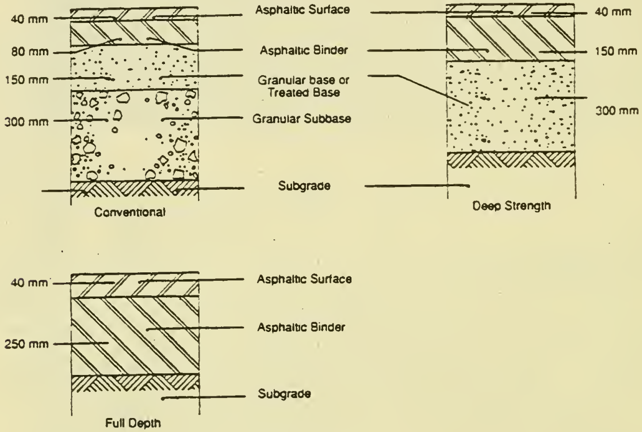
*** See Appendix G for terminology.

The pavement surface is normally hot-mix asphalt concrete (HMA), portland cement concrete (PCC), plant or road-mixed mulch, cold mix or surface treatment.

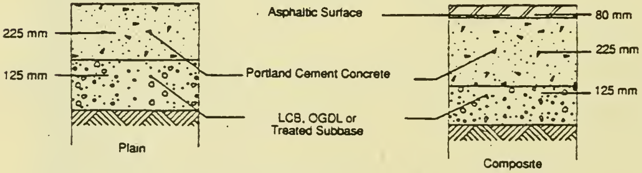
C2.2 Functions and Characteristics of Flexible Pavement Structure Layers

(A PCC surface distributes load stresses in addition to acting as a wearing surface.)

Wearing Course - Generally a dense, highly stable, durable, good frictional properties surface course HMA which carries the traffic. It must resist the elements and keep water out of the underlying materials. The surface course HMA type is selected on the basis of its wearing, durability, frictional and strength properties.



Flexible Pavements



Rigid Pavements

FIGURE C1 FLEXIBLE AND RIGID PAVEMENT STRUCTURES (MTO)

Binder Course - Lower layer(s) of HMA. Normally distinguished from the surface course when there is a difference in the quality of the hot mix used. It adds much to the overall strength of the pavement structure, supports the surface course and distributes load to the base.

The following mechanical properties are of importance to the performance of HMA:

1. elastic stiffness;
2. resistance to thermal cracking;
3. resistance to fatigue cracking; and
4. resistance to permanent deformation (rutting).

Granular Base Course - Carries a large portion of the load, provides some drainage, minimizes frost action and allows fine grading for surfacing. It is generally specified as high stability, graded, crushed gravel or stone.

Granular Subbase Course - Normally a non-processed aggregate obtained from local gravel pits. Performs the same function as a granular base course except that it can be of lower quality.

Subgrade - This is the 'foundation' for both flexible and rigid pavement structures. It is the uppermost material placed in embankments or remaining in cuts. It carries the pavement structure and distributed wheel load stresses.

C2.3 General Requirements for Aggregates in Pavements

Aggregates for use in granular subbase, granular base, treated base, HMA, PCC, etc. must be carefully specified/selected to perform satisfactorily in terms of function (vehicle load stresses for instance) and durability (frost resistance for instance). The Ontario grading and physical requirements for aggregates in pavements and transportation structures are typically based on MTO test procedures (LS), which simulate field conditions, and OPSS reflecting practical MTO usage experience.

C3. ASPHALT MATERIALS

C3.1 General

Asphalt materials include a wide range of plant and road mixes comprising asphalt binder (asphalt cement, cutback asphalt or emulsified asphalt) and aggregates, with the following general properties:

1. resistance to surface wear;
2. reduced surface water infiltration;
3. smooth and rideable finish; and
4. structural support of wheel loads.

The MTO defines two broad classes of asphalt pavement surfaces:

1. Mix Systems
   - hot and cold mixed asphalt concrete
   - hot and cold mixed stabilized base
   - recycled hot and cold mixed asphalt concrete
   - travel plant cold mix
   - slurry seal

2. Layered Systems
- penetration primer
- surface treatment
- macadam

Specific road/highway use, economic considerations and the functional requirements of the pavement type determine which asphalt material should be used to surface a road. The material and construction requirements for asphalt materials are typically covered by agency specifications (OPSS for instance).

C3.2 Hot-Mix Asphalt Concrete

Hot-mix asphalt concrete (HMA) is a designed (typically by Marshall method) mix of coarse and fine aggregates with asphalt cement binder which is mixed, placed and compacted in a heated condition. The MTO specifies (OPSS) a number of hot mix types:

HL 1 - dense-graded surface course mix, with a premium quality coarse aggregate (excellent frictional and wear properties, maximum 16 mm size), used on high-traffic volume highways.

HL 2 - sand mix (minus 9.5 mm) used as a levelling course, thin overlay on low speed areas and to fill wide cracks.

HL 3 - dense-graded surface course mix with aggregate gradation the same as HL 1 and lower physical properties requirements.

HL 3 Fine - fine, dense-graded surface course mix (minus 16 mm) used for hand work areas, minor municipal roads, driveways, boulevards, parking areas, etc.

HL 4 - dense-graded surface or binder course mix (minus 19 mm).

HL 8 - dense-graded binder course mix (minus 26.5 mm).

Recycled Hot Mix (RHM) - HL 4 and HL 8 binder course mixes incorporating up to 30 percent (or more) by mass reclaimed asphalt pavement (RAP).

Medium Duty Binder (MDBC) - dense-graded, high-stability binder course mix (either upgraded coarse aggregates or polymer modified asphalt cement).

Heavy Duty Binder (HDBC) - dense-graded, high-stability binder course mix designed to resist rutting (100 percent crushed coarse and fine aggregates).

Dense Friction Course (DFC) - dense-graded, premium surface course mix, with high frictional resistance (HL 1 gradation, physical properties of superior coarse and fine aggregates, trap rock and dolomitic sandstone for instance), used for high-speed, high-traffic volume highways.

Open Friction Course (OFC) - open-graded, premium surface course mix, with superior quality aggregates, used in place of DFC where low tire noise desired (free draining with good frictional resistance).

Modified Mixes - hot mixes modified to suit required performance or the availability of materials (open-graded drainage layer (OGDL) for instance).

C3.3 Cold-Mix Asphalt Concrete

Cold mix is a mixture of emulsified asphalt and aggregates produced, placed and compacted at ambient temperature. Liquid asphalt (cutback) is also used, however emulsified asphalt is normally specified due to its lower cost. The use of cold mix (dense or open-graded) is generally restricted to low-volume roads, where hot-mix asphalt concrete surfaced pavements are not required.

C3.4 Surface Treatments

Surface treatments consist of an application of emulsified or cutback asphalt binder and select aggregate over a prepared granular base or existing surface. Following placement of the aggregate, the mixture is rolled and compacted to provide a driveable and dust-free surface. Emulsified asphalt is more commonly used than cutback asphalt due to its lower cost. This type of pavement surface is frequently used on light to medium volume roads which may or may not have an existing asphalt concrete surface.

C3.5 Other Asphalt Surface Treatments

Other types of asphalt surface treatments include mulch pavement, slurry seal, fog seal, primer, tack coat and granular sealing.

Slurry seal is a mixture of emulsified asphalt, well graded fine aggregate and mineral filler (cement for instance) applied in 3 to 6 mm layers. Slurry seal is applied over existing asphalt concrete pavement and is used to seal the pavement and prevent ravelling. This treatment is predominantly used by urban municipalities. As an extension to conventional slurry seals, micro-surfacing (crushed aggregate/polymer modified emulsion slurry seal) use is developing in Ontario.

C4. PAVEMENT REHABILITATION

C4.1 General

When a flexible pavement's serviceability (quality) becomes lower with use than considered to be the minimum acceptable level, and routine and major maintenance activities are not able to adequately address the problems, rehabilitation of the pavement becomes necessary. The recommended rehabilitation alternatives for each road will be dependent upon the riding quality and the type of distress(es) evident, its cause(s) and severity, as well as operational and planning considerations.

C4.2 Hot-Mix Resurfacing

Hot-mix resurfacing, in conjunction with other improvements, is a widely adopted principal rehabilitation alternative. The overlay thickness required will depend on the ride and structural condition of the existing roadway. Where settlements and distortions of the road surface preclude placement of a smooth overlay, padding or milling may be necessary. Consideration must also be given to treatment of any cracks or other deficiencies prior to the resurfacing.

C4.3 Partial-Depth Removal and Hot-Mix Resurfacing

The structural condition of the pavement may be acceptable, however, aging of the surface or surficial defects such as ravelling, segregation and stripping may dictate partial-depth removal and replacement of the asphalt concrete with hot mix or recycled hot mix. The material (RAP) removed (normally cold milled) from the existing pavement surface may be transported to a central plant for recycling.

C4.4 In-Place Recycling

In-place recycling involves scarification of the existing pavement surface, in-place processing (either hot or cold) of the scarified materials, possibly adding binder (with or without additives to improve the binder properties) and simultaneous placement of the processed material. Regardless of the process selected, candidate sections for in-place recycling must be thoroughly evaluated and the properties of the existing asphalt concrete determined (aggregate characteristics and asphalt cement properties in particular), noting that the finished in-place recycled pavement quality will be largely dependent upon these features.

Cold in-place recycling consists of cold milling the existing pavement surface and mixing with emulsified asphalt (possibly in conjunction with modifiers to improve/restore the former, aged asphalt cement properties). Integrated equipment trains are available for this process.

Hot in-place recycling consists of heating the existing asphalt concrete surface, scarification (with mixing and possible addition of new materials and rejuvenating agents in some processes) and reprofiling to produce a recycled asphalt pavement of comparable quality to plant recycled hot mix. Some processes are capable of simultaneous in-place recycling followed by an integral hot-mix overlay in a single operation.

C4.5 Full-Depth Removal and Replacement with Recycled Hot Mix (RHM)

Where the existing asphalt concrete is too distressed to overlay and too thin (approximately 80 mm) to be considered for in-place recycling, full-depth removal and replacement with recycled hot mix (RHM) should be considered. The exposed granular base can be reshaped after removing the asphalt concrete, strengthened with additional granular base as necessary, and then surfaced using RHM.

C4.6 Cold Mix

Cold-laid mixes are produced either through a Midland Mix Paver or a central plant. The Midland Mix Paver comprises a mobile plant which mixes and places aggregate and emulsified asphalt. Both open-graded and dense-graded mixes can be constructed using this process, with the open-graded mixes generally being more successful due to better coating of the aggregates. The open-graded mix tends to ravel under higher traffic volumes and generally requires a seal coat over the cold-mix surface.

C4.7 Surface Treatments

A surface treatment consists of a spray application of asphalt binder followed by the distribution of aggregates that are subsequently rolled into the binder. Surface treatments can be designated as single or double over a primed or unprimed surface. The selection of each depends on the traffic volumes, loads and operating speeds.

C4.8 Pulverization and Remixing Prior to Resurfacing

Pulverization and remixing involves pulverizing the existing pavement structure (up to 80 mm of asphalt concrete over granular base or 100 mm of surface treatment, or mulch, over granular base) to a maximum depth of 200 mm. This process thoroughly mixes the individual pavement layers into a relatively homogeneous mixture that can be compacted as granular base.

C5. PRODUCTION AND PLACEMENT OF HOT-MIX ASPHALT

C5.1 General

The processes involved in the production and placement of hot-mix asphalt (HMA) and recycled hot mix (RHM) can be summarized as:

1. crushing, screening (grading) and stockpiling the coarse (plus 4.75 mm sieve size) and fine (minus 4.75 mm sieve size) aggregates at wayside or commercial pits and quarries (OPSS 1001 and 1003);
2. crushing (sometimes graded) and stockpiling reclaimed asphalt pavement (RAP) at the hot-mix plant if RHM produced (OPSS 1154);
3. [completing Marshall method mix design (Asphalt Institute and MTO procedures), for the selected aggregates and asphalt cement (OPSS 1101), to determine aggregate proportions and job mix formula (JMF) for the mix type(s) (asphalt cement content and aggregate gradation)];
4. stockpiling and handling of the aggregates at the hot-mix plant (batch, drum or drum/batch type);
5. storage and handling of the asphalt cement (can be modified asphalt cement) at the hot-mix plant;
6. [safety, environmental control and environmental stewardship at materials suppliers, during materials transport, at the hot-mix plant, at the paving site and during HMA/RHM production, transport, placing and compaction];
7. [verification of job mix formula (JMF) at the hot-mix plant (trial batch)];
8. proportioning (volumetric), drying and heating aggregates (drier for batch plant, drum for drum plant);
9. mixing dry, hot aggregates (mass of each hot bin for batch plant, overall belt scale mass for drum plant) and RAP, if incorporated (typically added to pug mill for batch plant or mid-drum for drum plant), with hot asphalt cement to JMF (plus additives, if any);
10. storing HMA or RHM in silo(s) and/or transporting to paving site;
11. placing HMA or RHM with paver on prepared surface;
12. compacting (rolling) hot laid HMA or RHM mat to desired density (static and/or vibratory steel wheeled roller(s) and rubber tired roller);
13. [quality control (QC) by contractor to ensure that HMA or RHM provided will meet specifications]; and
14. [quality assurance (QA) by owner to check that HMA or RHM specifications have been met].

As hot-mix asphalt (HMA), the Marshall method of HMA mix design and HMA/RHM production are very important to the use of crumb rubber modifier (CRM), these will be described in more detail.

C5.2 Hot-Mix Asphalt (HMA)

Hot-mix asphalt (HMA) is a combination of coarse and fine aggregates uniformly mixed and coated with asphalt cement. The aggregates and asphalt cement are heated prior to proportioning and mixing them together in a batch, drum or drum/batch plant. This is to provide both dry, hot aggregates and sufficient fluidity (temperature-viscosity relationship) to the asphalt cement which is a semi-solid at ambient temperatures. The HMA is then transported to the paving site, placed with a paver and compacted with rollers. Haul trucks should have clean, dent-free boxes, use a non-solvent asphalt release agent, be insulated, and tarped as appropriate. Proper paver operation is important to achieving the desired mat thickness, crown and smoothness. Proper compaction is critical to asphalt concrete pavement performance, with a minimum of 97 percent (of Marshall compliance density) typically specified for municipal projects.

The three components of HMA are aggregates, asphalt cement and air. Aggregates are the largest component by far of HMA, generally 93 to 96 percent by mass, or 78 to 86 percent by volume, and 'carry' the load through particle interaction. Aggregates for potential use in HMA are generally evaluated in terms of: size and grading; cleanliness; soundness; toughness; shape; surface texture; absorption; affinity for asphalt cement; and frictional properties (surface course). These gradation and physical requirements for aggregates use in HMA are generally covered by OPSS, for instance the OPSS 1150 HMA gradation requirements for municipal projects in Table C1. Gradings are selected to avoid tender (unstable) and harsh mixes as shown in Figure C2, while providing adequate voids mineral aggregate (VMA) for the asphalt cement. For crumb rubber modifier (CRM) use in HMA (RUMAC), it is critical that the mix gradation is adjusted (volumetrically) to accommodate the CRM. The MTO has aggregate sources lists (ASL) and designated materials lists (DSL) for their HMA projects.

Asphalt cement, generally 4 to 7 percent by mass (and volume) of HMA, binds the aggregate particles together, providing workability during placement/compaction and asphalt concrete durability, fatigue resistance and flexibility. Asphalt cement is currently selected by penetration grade (Table C2) in Ontario. In Southern Ontario, 85/100 penetration grade is used, with softer grades (higher penetration) in colder parts of Ontario. However, it is very important to note that penetration alone is not an adequate descriptor of potential asphalt cement behaviour, as it is the temperature susceptibility (Figure C3) that influences deformation and thermal cracking resistance. This is recognized in Canadian General Standards Board (CGSB) asphalt cement specifications (CAN/CGSB-16.3). Crumb rubber modifier (CRM) use as an asphalt cement modifier (AR) has been shown to significantly reduce the temperature susceptibility of the modified asphalt cement, which should give more resistance to deformation and thermal cracking.

The third component of HMA, air voids (AV), makes up about 4 percent of the HMA at the mix design stage, and typically 6 to 8 percent of the compacted asphalt concrete. Some air voids are necessary to prevent flushing (about 4 percent in traffic densified asphalt concrete), but too many voids 'weaken' the asphalt concrete and decrease its durability.

The job mix formula (JMF) aggregate gradation and asphalt cement content for an HMA is typically based on the Marshall method of mix design as summarized in Figure C4. The objective of the Marshall method of HMA mix design is to develop the optimal mix (aggregates, asphalt cement and air voids) for the selected materials meeting the applicable specification.

SIEVE DESIGNATION	PERCENTAGE PASSING BY DRY MASS				
	HL 1 and 3	HL 2	HL 3A	HL 4	HL 8
26.5 mm					100
19.0 mm				100	94 - 100
16.0 mm	100		100	98 - 100	77 - 95
13.2 mm	98 - 100		98 - 100	83 - 95	
9.5 mm	75 - 90	100	85 - 94	62 - 82	48 - 78
4.75 mm	45 - 65	85 - 100	65 - 80	40 - 67	30 - 55
2.36 mm	36 - 64	70 - 90	52 - 80	27 - 66	21 - 54
1.18 mm	25 - 58	50 - 75	36 - 72	16 - 60	12 - 49
600 μm	16 - 45	30 - 55	23 - 56	8 - 47	6 - 38
300 μm	7 - 26	15 - 35	10 - 32	4 - 27	3 - 22
150 μm	3 - 10	5 - 16	3 - 12	1 - 10	1 - 9
75 μm	0 - 5	3 - 8	0 - 6	0 - 6	0 - 6

TABLE C1 OPSS 1150 HMA GRADATION REQUIREMENTS (OPSS)
(OPSS 1150 is Used for Municipal Projects and OPSS 1149 is Used for MTO Projects.)

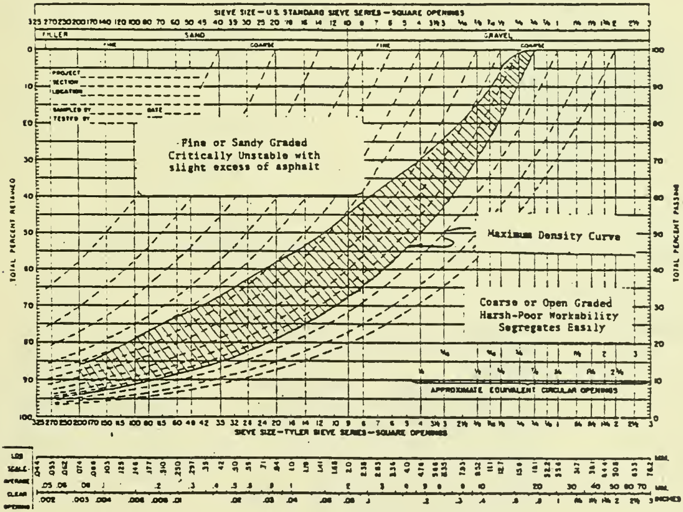
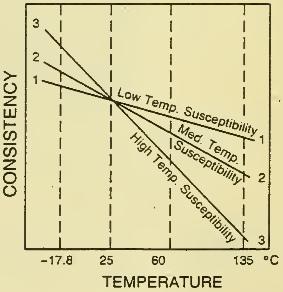


FIGURE C2 STANDARD GRADING CHART SHOWING MAXIMUM DENSITY CURVES AND ZONES OF POTENTIALLY TENDER (UNSTABLE) AND HARSH MIXES

PENETRATION GRADE	60/70		85/100		150/200		300/400		TEST METHOD
REQUIREMENTS	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
Flash Point (C.O.C.)°C	232	--	232	--	218	--	177	--	MTO LS-201
Penetration (at 25°C 100g, 5 s) 0.1 mm	60	70	85	100	150	200	300	400	MTO LS-200
Kinematic Viscosity (at 135°C) mm²/s	360	--	280	--	200	--	120	--	MTO LS-202
Ductility (at 4°C, 1 cm/min) cm	4	--	6	--	10	--	15	--	MTO LS-205
Solubility in Trichloroethylene, % by mass	99.5	--	99.5	--	99.5	--	99.5	--	MTO LS-204
Thin Film Oven Test									
% Loss in Mass (50 ml, 163°C,5 hrs.)	--	0.80	--	0.85	--	1.3	--	1.3	ASTM D-1754
% Retained Pen. at 25°C	52	--	47	--	42	--	35	--	ASTM D-1754
Ductility of Residue (at 25°C, 5 cm/min) cm	50	--	75	--	100	--	100	--	MTO LS-205

TABLE C2 OPSS 1101 HMA ASPHALT CEMENT REQUIREMENTS (OPSS)

FIGURE C3 THE CONCEPT OF ASPHALT CEMENT TEMPERATURE SUSCEPTIBILITY (McLEOD)
(The Three Asphalt Cements Have the Same Penetration at 25°C. Asphalt Cement 1 Has the Lowest Temperature Susceptibility (Higher Viscosity at 60 and 135°C), and Will be More Resistant to Deformation at High Temperatures and Thermal Cracking at Low Temperatures.)



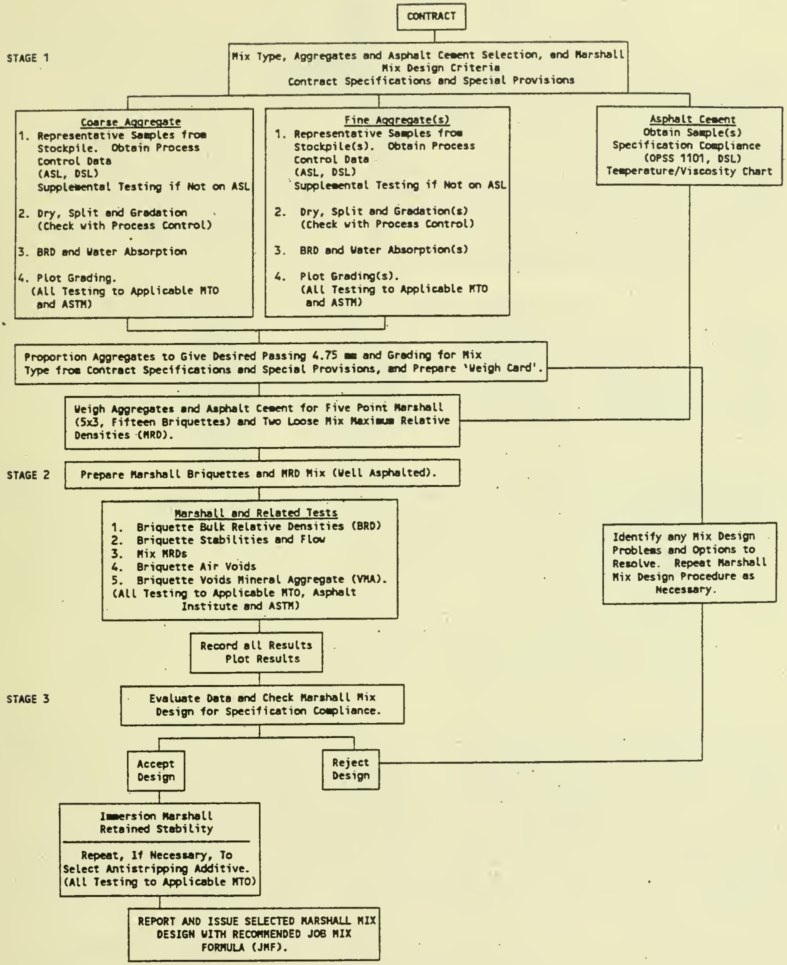

CONTRACT
STAGE 1
Mix Type, Aggregates and Asphalt Cement Selection, and Marshall Mix Design Criteria
Contract Specifications and Special Provisions
Coarse Aggregate
1. Representative Samples from Stockpile. Obtain Process Control Data (ASL, DSL) Supplemental Testing if Not on ASL
2. Dry, Split and Gradation (Check with Process Control)
3. BRD and Water Absorption
4. Plot Grading. (All Testing to Applicable MTO and ASTM)
Fine Aggregate(s)
1. Representative Samples from Stockpile(s). Obtain Process Control Data (ASL, DSL) Supplemental Testing if Not on ASL
2. Dry, Split and Gradation(s) (Check with Process Control)
3. BRD and Water Absorption(s)
4. Plot Grading(s). (All Testing to Applicable MTO and ASTM)
Asphalt Cement
Obtain Sample(s)
Specification Compliance (OPSS 1101, DSL)
Temperature/Viscosity Chart
Proportion Aggregates to Give Desired Passing 4.75 mm and Grading for Mix Type from Contract Specifications and Special Provisions, and Prepare 'Weigh Card'.
Weigh Aggregates and Asphalt Cement for Five Point Marshall (5x3, Fifteen Briquettes) and Two Loose Mix Maximum Relative Densities (MRD).
STAGE 2
Prepare Marshall Briquettes and MRD Mix (Well Asphalted).
Marshall and Related Tests
1. Briquette Bulk Relative Densities (BRD)
2. Briquette Stabilities and Flow
3. Mix MRDs
4. Briquette Air Voids
5. Briquette Voids Mineral Aggregate (VMA).
(All Testing to Applicable MTO, Asphalt Institute and ASTM)
Identify any Mix Design Problems and Options to Resolve. Repeat Marshall Mix Design Procedure as Necessary.
Record all Results
Plot Results
STAGE 3
Evaluate Data and Check Marshall Mix Design for Specification Compliance.
Accept Design
Reject Design
Immersion Marshall Retained Stability
Repeat, If Necessary, To Select Antistripping Additive. (All Testing to Applicable MTO)
REPORT AND ISSUE SELECTED MARSHALL MIX DESIGN WITH RECOMMENDED JOB MIX FORMULA (JMF).

FIGURE C4 MARSHALL METHOD MIX DESIGN PROCEDURE FLOW CHART (MTO/JEGEL) (ASTM D1559, ASPHALT INSTITUTE MS-2 and MTO.)

C5.3 Marshall Method of Mix Design

The mix design method and design requirements form an essential aspect of the specification for any asphalt paving such as the Ontario crumb rubber modifier (CRM) demonstration projects summarized in Appendix B. For Ontario, the standardized Marshall method of mix design (ASTM D1559, Asphalt Institute (AI MS-2) and MTO LS) and OPSS design requirements (plus special provisions as necessary) have been adopted (Figure C4) with considerable practical experience and success. The Marshall method is generally applicable for the volumetric proportioning of dense-graded hot-mix asphalt, with a maximum coarse aggregate size of 25 mm (comparable equipment has been developed for large stone mixes), incorporating penetration or viscosity graded asphalt cement (or modified asphalt cement). It can be used for both the laboratory design (JMF) and the field control of hot-mix asphalt paving.

The principal features of the method are density-voids analyses of the aggregates, asphalt cement and air voids system (Figures C5 and C6) and stability-flow tests on specimens (briquettes) of compacted mix 'representative' of the proportioning, placing and compacting of hot-mix asphalt. It is not a performance-based method, but rather an empirical approach to the selection of aggregate proportions (gradation) and asphalt cement content meeting air voids (AV), voids mineral aggregate (VMA), stability and flow requirements associated with 'satisfactory' asphalt concrete.

The Marshall method starts with the preparation of briquettes. Preliminary to this procedure, it is necessary that the:

a. aggregates and asphalt cement (and additives, if any) meet the project specification requirements (typically OPSS 1001 and 1003 for aggregates and Table C2 for asphalt cement);
b. temperature-viscosity relationship for the asphalt cement is available (Figure C3);
c. aggregate gradation (proportions) meets the project specification requirements (typically Table C1, noting Figure C2); and
d. bulk specific gravity of all materials used in the mix are known or determined (Figure C5).

Standard briquettes (64 mm high by 102 mm diameter) are prepared using a specified procedure for heating, mixing (at about 150°C) and compacting (at about 140°C for 85/100 penetration grade asphalt cement, typically 75 blows/face with a manual compaction hammer or mechanical equivalent) the aggregate-asphalt cement mix. In order to determine the 'optimum' asphalt cement content, triplicate briquettes are prepared at 0.5 percent asphalt cement content increments (five points about the anticipated design content) to give well-defined plots (Figure C7) of bulk relative density (BRD), maximum relative density (MRD, determined on separate loose mix), AV, VMA, stability and flow against asphalt cement content. The typical design asphalt cement content of HL binder course mixes is 4.5 to 5.0 percent and HL surface course mixes is 5.0 to 6.0 percent.

The stability of a briquette is the maximum 'load' resistance in Newtons developed for the briquette in a special diametral loading head at 60°C. The flow value in 0.25 mm units is the total vertical deformation of the briquette during the stability tests. Trends generally noted for dense-graded hot-mix asphalt (Figure C7) with increasing asphalt cement content, are:

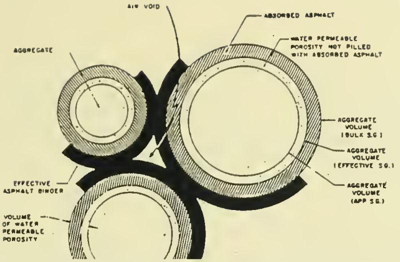
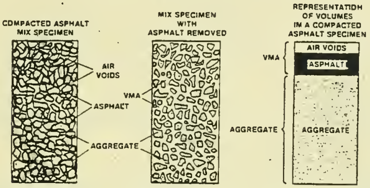

AIR VOID
ABSORBED ASPHALT
AGGREGATE
WATER PERMEABLE POROSITY NOT FILLED WITH ABSORBED ASPHALT
AGGREGATE VOLUME (BULK S.G.)
AGGREGATE VOLUME (EFFECTIVE S.G.)
AGGREGATE VOLUME (APP S.G.)
EFFECTIVE ASPHALT BINDER
VOLUME OF WATER PERMEABLE POROSITY

FIGURE C5 SCHEMATIC OF AGGREGATE, ASPHALT CEMENT AND AIR VOID. THE EFFECTIVE ASPHALT CEMENT CONTENT (BLACK THICK FILMS) IS VERY IMPORTANT TO HMA PERFORMANCE (AI)
(The Aggregate ASTM Bulk Specific Gravities Are Used in VMA Calculations. Need Adequate VMA to Allow For Incorporation of Sufficient Asphalt Cement.)


COMPACTED ASPHALT MIX SPECIMEN
MIX SPECIMEN WITH ASPHALT REMOVED
REPRESENTATION OF VOLUMES IN A COMPACTED ASPHALT SPECIMEN
AIR VOIDS
ASPHALT
AGGREGATE
VMA
AIR VOIDS
ASPHALT
VMA
AGGREGATE
AGGREGATE

NOTE: For Simplicity the Absorbed Asphalt Cement is Not Shown.

FIGURE C6 THREE COMPONENTS (AGGREGATES, ASPHALT CEMENT, AIR) OF HOT-MIX ASPHALT (HMA) AND VOIDS MINERAL AGGREGATE (VMA) IN COMPACTED MIX (AI)
(VMA is the Sum of the Air Voids Volume and Effective (Non-Absorbed) Asphalt Cement Volume.)

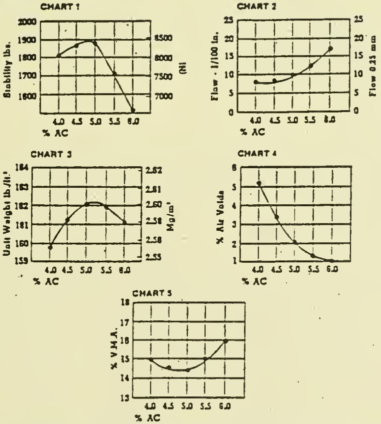


FIGURE C7 EXAMPLE (US) MARSHALL METHOD CURVES SHOWING TEST RESULTS FOR FIVE ASPHALT CEMENT CONTENTS (AI)

a. stability increase up to a maximum and then decreases
b. flow increases, more steeply as the maximum BRD is passed;
c. BRD curve is similar to that for stability, except that the maximum BRD generally occurs at a somewhat higher asphalt cement content;
d. AV decrease, ultimately approaching a minimum; and
e. VMA generally decreases to minimum value and then increases.

The optimum (design) asphalt cement content is generally taken at the median of the specification AV range (typically 4±0.5 percent for most HL mixes with specification AV of 3 to 5 percent), providing the minimum stability, flow and VMA requirements are satisfied. It may be necessary to vary the aggregate proportions, types and/or sources, and repeat the Marshall mix design, in order to meet all of the specification requirements which often also include minimum asphalt cement content and percent passing 4.75 mm sieve size requirements.

The Marshall method is also used for the design of RHM. In the case of RHM, another 'aggregate' with some old asphalt cement content, is involved during the mix design which requires RAP testing (gradation, asphalt cement content and asphalt cement penetration/viscosity) and consideration of fine blend sands and softer asphalt cements.

C5.4 Production of Hot-Mix Asphalt (HMA) and Recycled Hot Mix (RHM)

C5.4.1 General

The two hot-mix asphalt plant types used for the Ontario CRM demonstration projects summarized in Appendix B were batch and drum (drum mixer) with either a dry (baghouse) or wet (scrubber) collector system for environmental control of fine particulate material. A third type of hot-mix plant used in Ontario - drum/batch - combines the features of drum and batch plants. The moisture removal, heating and coating functions of batch and drum plants are shown in Figure C8. Typical batch plant (with baghouse) and drum plant (with scrubber) descriptions, as required in applications for MOEE Certificates of Approval (Air), will be used to indicate the main features of HMA/RHM production.

C5.4.2 Batch Plant

A schematic of a typical batch-type hot-mix asphalt plant with dry collector (baghouse) is given in Figure C9 along with a materials flow diagram in Figure C10. The batch plant can be either a portable or stationary installation, with the drier burner fired using fuel oil (portable) or natural gas. A separate hot oil heater is used to heat the asphalt cement storage tank(s) and lines.

At the batch plant, the damp, cold aggregates (typically about 50 percent coarse aggregate and 50 percent fine aggregate) are drawn from the cold feed bins and conveyed into the rotary drier, with the proportions of each aggregate initially controlled by the cold feed bin gate openings and the speed of the feed conveyor. The dry hot aggregates (approximately 160°C) from the drier are carried up the plant hot elevator to the top of the batch tower horizontal vibrating screen deck. The screens separate the aggregate into three (sometimes four) size fractions, plus oversize, in separate hot feed bins, rejecting any oversized aggregate through a chute. Under computer (operator) control, the aggregate is proportioned by mass from each hot feed bin into the aggregate batcher. At the same time, heated asphalt cement (approximately 150°C) or modified asphalt cement (AR, for instance, at the appropriate temperature) is pumped from the storage tank and dispensed by mass into the asphalt cement batcher. The

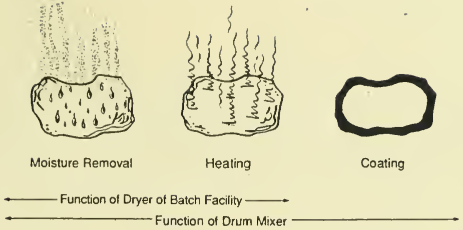


FIGURE C8 MOISTURE REMOVAL (DRYING), HEATING AND COATING OF AGGREGATE WITH ASPHALT CEMENT FUNCTIONS OF BATCH AND DRUM PLANTS (NAPA)

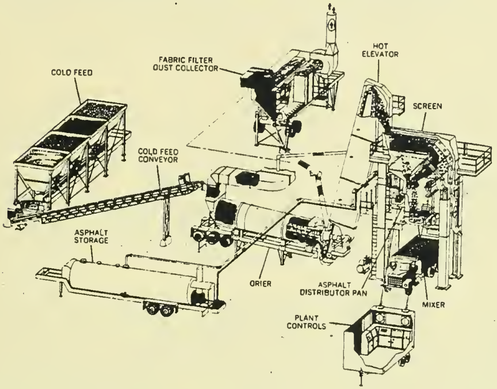


FIGURE C9 SCHEMATIC OF PORTABLE PLANT WITH DRY COLLECTOR (FABRIC FILTER BAGHOUSE) (MTO)

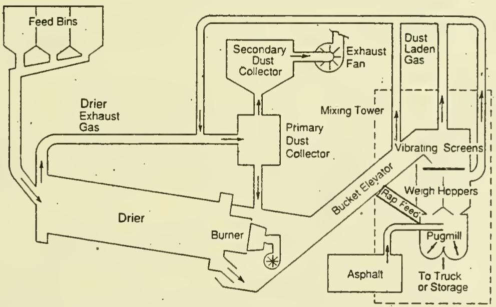


FIGURE C10 MATERIALS FLOW DIAGRAM FOR BATCH PLANT (RAP FEED CAN BE USED AS CRM ADDITION POINT) (NAPA)

aggregate batcher then discharges the aggregates into the empty pugmill mixer for dry mixing (about 10 seconds). (Additional materials, such as mineral filler, RAP for RHM and/or CRM for RUMAC, can be proportioned by mass into the mixer at this stage.) The asphalt cement batcher then discharges the asphalt cement into the pugmill mixer for wet mixing (about 30 seconds) to give a uniform hot-mix asphalt (HMA). The pugmill gate is then opened and the HMA (approximately 145°C for mix incorporating 85/100 penetration grade asphalt cement) falls into the truck box below for transport to the paving site(s), or can be conveyed to a hot-mix storage silo for temporary storage (generally less than 24 hours). The batch cycle is then repeated. All of the batch plant operations are monitored and controlled from instruments in the control trailer. The emissions (fine particulate and water vapour) are discharged through a dry collector system (standard primary collector and fabric filter baghouse) in accordance with the plant's Certificate of Approval (Air).

C5.4.3 Drum Plant

A schematic of a typical drum-type hot-mix asphalt plant with wet collector (scrubber) is given in Figure C11 along with a materials flow diagram in Figure C12. It should be particularly noted that crumb rubber modifier (CRM) for RUMAC should not be added through the drum (drum mixer) RAP bin (Figure C12), but rather through a CRM feed system (Figure C13) into the drum after the asphalt cement is added. This will both keep the CRM away from the drum burner flame and avoid entrainment into the drum exhaust gas. The drum plant can be either a portable or stationary installation, with the drum burner fired using fuel oil or natural gas.

At the drum plant, the damp, cold aggregates are drawn from the cold feed bins in the required volumetric proportions on to a cold-feed conveyor. An automatic weigh-in-motion system (also for RAP addition if RHM production) monitors the mass of aggregate flowing into the drum (drum mixer). The aggregates are dried and heated (approximately 160°C) in the first part of the drum. The dry, heated aggregate is then mixed with asphalt cement in the second part of the drum as a continuous process. The asphalt storage pump control is interlocked to the aggregate 'weighing' system to correctly proportion the asphalt cement (approximately 150°C) or modified asphalt cement (AR, for instance, at the appropriate temperature). The aggregate and asphalt cement are thoroughly mixed by the drum's rotating action. From the drum, the HMA is transported by a slat conveyor to a storage silo from which it is loaded into trucks for transport to the paving site(s). The emissions (fine particulate and water vapour) are discharged through a wet collector system (standard primary collector and scrubber). The wet scrubber uses the differential between high velocity gases and a fine spray of water to remove particulate from the exhaust gas. The fine particulate matter removed in the wet scrubber system flows to the scrubber pond(s) where it drops out of suspension so that the water can be recirculated along with make-up water. Settled fine particulate material (sludge) is disposed of as inert fill. This overall emissions control system is operated in accordance with the plant's Certificate of Approval (Air).

C6. ASPHALT CONCRETE PAVEMENT DISTRESS

It is normal to monitor the condition of a pavement over time to determine the appropriate maintenance strategy. For demonstration projects such as crumb rubber modifier (CRM) use in hot-mix asphalt (RUMAC), or in modified asphalt cement (AR), the short and long-term asphalt concrete pavement performance monitoring requires distress identification (type, severity and extent) as part of the overall pavement assessment. For Ontario, this typically involves the use of

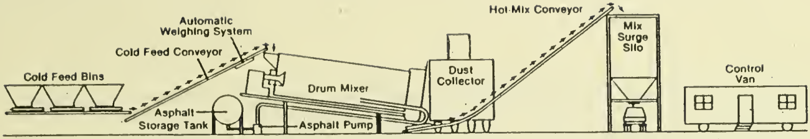


FIGURE C11 SCHEMATIC OF PORTABLE DRUM PLANT WITH WET COLLECTOR (SCRUBBER) (AI)

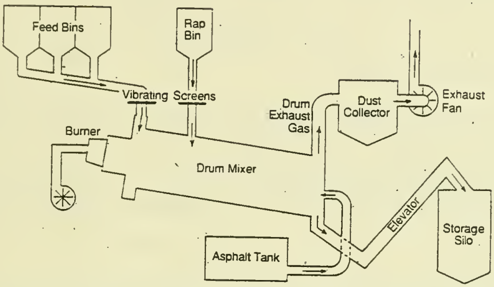


FIGURE C12 MATERIALS FLOW DIAGRAM FOR DRUM PLANT (RAP BIN SHOULD NOT BE USED FOR CRM ADDITION) (NAPA)

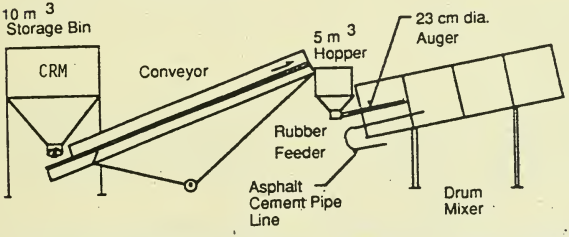


FIGURE C13 FEED SYSTEM FOR CRM ADDITION IN DRUM PLANT, HURON CONSTRUCTION, THAMESVILLE (MTO)

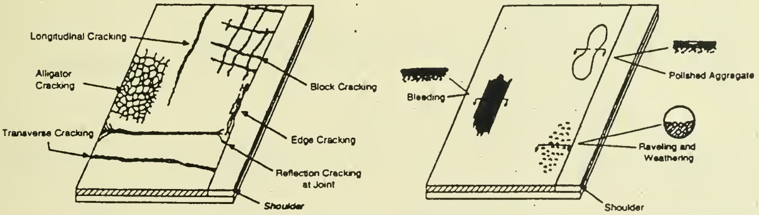


FIGURE C14 ASPHALT CONCRETE PAVEMENT DISTRESS TYPES - CRACKING AND SURFACE DEFECTS (SHRP)

MTO pavement distress manuals ("Condition Rating of Flexible Pavements - Distress Manifestations" and "Flexible Pavement Condition Rating - Guidelines for Municipalities"). An indication of the cracking and surface defect distress types is given in Figure C14, as developed for the Strategic Highway Research Program, (SHRP) long term pavement studies. Other distress types include surface deformation (rutting and shoving), patching and potholes.

C7. REFERENCES

C7.1 Specifications and Uses

The current edition of these references should be consulted as specifications and manuals are always subject to revision.

ASTM, "Construction", Annual Book of ASTM Standards:
Volume 04.02/Concrete and Aggregates;
Volume 04.03/Road and Paving Materials; Pavement Management Technologies; and
Volume 04.04/Roofing, Waterproofing, and Bituminous Materials;

MTO, "Specifications and Special Provisions", Contract Design, Estimating and Documentation Manual, Volume 2, Chapter E, Ontario Ministry of Transportation, Downsview, current.

MTO, "Coarse Aggregates for HL1 and DFC", Designated Sources for Materials, DSM Number 3.05.25, current.

MTO, Laboratory Testing Manual, current.

OPSS, Ontario Provincial Standards, Ministry of Transportation, Municipal Engineers Association and Ministry of Environment, Ontario Provincial Standards Section, Ontario Ministry of Transportation, Downsview, current:
OPSS 1001, Material Specification for Aggregates - General;
OPSS 1003, Material Specification for Aggregates - Hot Mixed, Hot Laid, Asphaltic Concrete;
OPSS 1101, Material Specification for Asphalt Cement;
OPSS 1149, Material Specification for Hot Mixed, Hot Laid Asphaltic Concrete Including Recycled and Speciality Mixes (intended for MTO projects);
OPSS 1150, Material Specification for Hot Mixed, Hot Laid, Asphaltic Concrete;
OPSS 1154, Material Specification for Hot Mixed, Hot Laid, Asphaltic Concrete Containing Reclaimed Asphalt Pavement; and
OPSS 1155, Material Specification for Medium Duty Binder Course Asphaltic Concrete.

C7.2 General Design Manuals and Handbooks

AI, "The Asphalt Handbook", Manual Series No. 4, 1989 Edition, Asphalt Institute, Lexington, 1989.

AI, "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types", Manual Series No. 2, 1988 Printing, Asphalt Institute, Lexington, 1989 (and Addenda).

MTO, Pavement Design and Rehabilitation Manual, Ontario Ministry of Transportation, Downsview, January 1990.

NAPA, "The Fundamentals of the Operation and Maintenance of the Exhaust Gas System in a Hot Mix Asphalt Facility", Gunkel, K.O., Second Edition, Information Series 52/87, Revised 1986/87, National Asphalt Pavement Association, Lanham, 1989.

NCAT, "Hot Mix Asphalt Materials, Mixture Design, and Construction", Roberts, F.L. et al, National Center for Asphalt Technology, NAPA Education Foundation, Lanham, 1991.

C7.3 Crumb Rubber Modifier (CRM) Use in Asphalt Paving Projects

FHWA, "State of the Practice - Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier", Heitzman, M.A., FHWA-SA-92-022, Federal Highway Administration, Washington, 1992.

APPENDIX D

EXAMPLE DRAFT SPECIAL PROVISION FOR RUMAC

____

EXAMPLE ONLY
DRAFT

SPECIAL PROVISION FOR RUBBER MODIFIED HOT-MIX ASPHALT (RUMAC) - DRY PROCESS
HL _ (RUMAC) BINDER COURSE AND HL _ (RUMAC) SURFACE COURSE

1.0 SCOPE

This Special Provision covers the supplemental requirements to OPSS 310 (Construction Specification for Hot Mixed, Hot Laid Asphaltic Concrete Paving and Hot Mix Patching) and OPSS 1150 (Material Specification for Hot Mixed, Hot Laid Asphaltic Concrete) for the materials, equipment and methods to be followed for proportioning, mixing, placing and compacting rubber modified hot-mix asphalt (RUMAC). This is commonly referred to as the generic dry process for incorporating recycled scrap tire crumb rubber (CRM) in hot-mix asphalt.

Two rubber modified hot-mix asphalt types are specified in the Contract:

HL _ (RUMAC) Binder Course Mix -	incorporating ___* percent CRM (___* Mesh) by total mix mass, with a ______ penetration grade asphalt cement content of ___* percent by total mix mass for tendering purposes; and
HL _ (RUMAC) Surface Course Mix -	incorporating ___* percent CRM (___* Mesh) by total mix mass, with a ______ penetration grade asphalt cement content of ___* percent by total mix mass for tendering purposes.

Payment will be adjusted for the actual Job Mix Formula asphalt cement content of the RUMAC mixes, from the asphalt cement contents for tendering purposes, as covered in Section 7.2 of this Special Provision.

2.0 MATERIALS

2.1 Supply of Materials

With the exception of the crumb rubber (CRM), the Contractor shall supply all materials necessary for the execution and completion of the Contract.

________________________________ will supply the CRM, FOB the Contractor's hot-mix plant on trucks, in ___* pound bags (plastic, non-heat melt), ___* bags to the pallet (shrink plastic covered). It shall be the Contractor's responsibility for unloading the pallets and storing the CRM such as there is no physical or environmental damage to the CRM.

* [Design Guide - Some current projects incorporate 1.5 percent CRM (No. 10 Mesh) in surface course and 3.0 percent CRM (No. 10 Mesh) in binder course. Trend is to less and finer CRM.
- The asphalt cement content of RUMAC is about 0.6 to 0.7 percent greater per 1.0 percent of CRM incorporated, compared to conventional hot-mix asphalt of the same type.
- CRM typically shipped in 50 pound bags, 40 bags to the pallet.]

2.2 **Asphalt Cement**
Asphalt cement shall comply with OPSS 1101 (Material Specification for Asphalt Cement). The asphalt cement penetration grade shall be ______.

2.3 **Coarse Aggregate(s)**
Coarse Aggregate(s) (aggregate retained on the 4.75 mm) shall meet the requirements of OPSS 1001 (Material Specification for Aggregates - General) and OPSS 1003 (Material Specification for Aggregates - Hot Mixed, Hot Laid, Asphaltic Concrete).

2.4 **Fine Aggregate(s)**
Fine Aggregate(s) (aggregate passing the 4.75 mm) shall meet the requirements of OPSS 1001 and OPSS 1003.

2.5 **Crumb Rubber (CRM)**
Crumb rubber (CRM) will be supplied by ____________ as described in Section 2.1 of this Special Provision.

2.6 **Additives**
Antistripping additive, if required, shall be as indicated by type and amount on the Job Mix Formula for the RUMAC mixes. When an antistripping additive is required, it shall be supplied and used at the Contractor's cost.

3.0 JOB MIX FORMULA (JMF)

3.1 **Contractor Submittals**
The Contractor shall, within two working days of Contract award, advise the ______ (Engineer), in writing, of the sources of asphalt cement, coarse aggregate(s), fine aggregate(s) and antistripping additive, if any. The Contractor should also advise the Engineer, at this time, of factors such as previous experience with the materials and HL _ mix designs that will be of assistance to the Engineer in having mix designs completed.

The Contractor shall, within four working days of Contract award, supply the Engineer with 75 kg of each aggregate, 5 kg of fines (minus 75 μm), if any to be added to mix design, 4 ℓ of asphalt cement, 0.1 ℓ of antistripping additive, if any to be used (or equivalent amount of hydrated lime), and the temperature-viscosity chart for the asphalt cement.

3.2 **Mix Designs**
The Engineer will complete Marshall method mix designs (Ministry of Transportation procedures, AI MS-2) for the RUMAC mixes, using the materials and information submitted by the Contractor. The Job Mix Formula for each RUMAC mix will be based on these mix designs. These mix designs will be completed within 7 working days of materials submittal.

3.3 **Job Mix Formula (JMF)**
The Engineer will provide the Contractor with the Job Mix Formula (JMF) for the HL _ (RUMAC) Binder Course mix and HL _ (RUMAC) Surface Course mix upon completion of the mix designs.

The JMF will specify the source, composition and proportion of the aggregates, CRM, asphalt cement and antistripping additive, if any, for each RUMAC mix. The JMF for each RUMAC mix shall be in effect until modifications, if any, are approved by the Engineer.

4.0 TRIAL BATCHES

The Contractor shall make pre-construction plant trial batches of the RUMAC mixes from which samples will be taken by the Engineer to ensure that each RUMAC mix meets the requirements of its JMF. Each trial batch shall be representative of consistent mix production. Such RUMAC trial batches shall be produced until a complete mix compliance check indicates conformance with the JMF proportions and properties of the mix. The trial batches shall be paid at the Contract price for HL _ (RUMAC) Binder Course and HL _ (RUMAC) Surface Course.

5.0 CONSTRUCTION REQUIREMENTS

5.1 Weather Limitations

The RUMAC mixes shall only be placed under the following minimum conditions and when weather conditions will permit proper construction.

For compacted thickness less than 40 mm	
ambient air temperature	15°C and rising
surface temperature	15°C minimum
surface condition	dry

For compacted thickness 40 mm and greater	
ambient air temperature	10°C and rising
surface temperature	10°C minimum
surface condition	dry

5.2 Equipment

Equipment used for the production, placement and compaction of RUMAC mixes shall conform to OPSS 310 and OPSS 1150 with the following modifications:

The hot-mix plant shall have automatic controls that coordinate the proportioning, timing and discharge of the hot-mix asphalt. The hot-mix plant shall be capable of uniformly feeding and measuring the amount of crumb rubber (CRM) placed into the pug mill or mixing chamber. The Contractor shall obtain all necessary approvals, such as MOEE Certificate of Approval (Air) inclusion of RUMAC production, for the hot-mix plant.

Transporting RUMAC mixes on rubber belts is prohibited.

Drum mixing facilities shall not add the CRM to the aggregate cold feed system. The CRM must be added beyond the aggregate drying and heating section of the mixing chamber.

The hauling equipment and compaction rollers shall be thinly coated with a light application of a non-petroleum based wetting agent (soap solution) to reduce sticking of the mixture to the equipment. Oiling the surfaces with kerosene or diesel fuel will not be permitted.

Pneumatic-tired rollers will not be used*.

* [Design Guide - There have been problems with pick-up and shoving with the use of pneumatic-tired rollers.]

5.3 Surface Preparation

Pavement surface preparation shall conform to OPSS 310.

5.4 Mixing, Placing and Compaction

Mixing, placing and compaction of each RUMAC mix shall conform to the JMF and OPSS 310 and OPSS 1110 with the following modifications:

When the production method uses units (bags) of CRM for proportioning at a hot-mix batch plant, the batch size and CRM unit size shall be adjusted to use whole units (bags) of CRM. Adding partial units (bags) of CRM into the mix will not be permitted.

For hot-mix batch plants, the CRM shall be incorporated into the mix prior to the addition of asphalt cement. The dry mixing cycle shall be increased as necessary to ensure that all of the CRM is properly mixed with the aggregates. The wet mixing time shall be increased as necessary over conventional mixes to produce a homogeneous mix.

The Contractor will take care to ensure that the CRM bags are fully opened and dumped out when incorporating CRM, and no fragments of bags are permitted to get into the mix. (The bags are not heat-melt type*.)

The RUMAC mixes discharge temperature from the plant shall be ___*°C.

The Contractor will take care with the initial compaction of the mix as RUMAC mixes have an initial low stability.

Finish rolling shall continue until the temperature of the mat drops below 60°C.

6.0 MEASUREMENT FOR PAYMENT

Measurement for payment of RUMAC mixes will be in tonnes conforming to OPSS 102 (Weighing of Materials). Trial batch quantities will be measured for payment.

7.0 BASIS OF PAYMENT

7.1 HL _ (RUMAC) Binder Course and HL _ (RUMAC) Surface Course

Payment at the Contract price for the above items shall be full compensation for all labour, equipment and materials required to do the work.

7.2 Payment Adjustment for Asphalt Cement Content

In the event that the actual JMF for the RUMAC mix(es) is different for asphalt cement content than that shown for tendering purposes in Section 1.0 of this Special Provision, an asphalt cement content adjustment will be applied. For each 0.1 percent more (less) asphalt cement content the payment per tonne of RUMAC mix(es) will be increased (decreased) by $ ___*.

* [Design Guide - Polymelt bags are available, but mixing problems have been experienced.
- Typically 5 to 10°C higher than conventional hot-mix asphalt.
- Typically $ 0.20. per tonne.]

APPENDIX E

GUIDE WORK PLAN FOR EVALUATION OF CRUMB RUBBER MODIFIER (CRM) ASPHALT PAVING MAJOR DEMONSTRATION PROJECTS

GENERAL

1. Adapted from FHWA State of the Practice - Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier (FHWA-SA-92-022, 1992, Appendix C References).

2. Concerned with technical feasibility, cost-effectiveness and environmental impacts of CRM asphalt paving compared to conventional asphalt paving controls.

3. There are four essential elements required for the evaluation of a specific CRM asphalt paving demonstration project:

pavement performance	1.	comparative CRM test and control sections as nearly identical as possible;
	2.	detailed information on the design, construction, performance and cost of these sections (performance throughout design life);
environmental impacts	3.	comparative CRM and control mix production runs under conditions as nearly identical as possible; and
	4.	detailed information on gaseous, particulate, liquid and solid emissions for these runs (including emissions with time from the sections).

DESIGN AND PRECONSTRUCTION TESTING DETAILS

The following information should be documented for both the test section(s) and the control section(s):

1. Pavement structural design data and assumptions (ADT, percent heavy vehicles, drainage, etc.);
2. Cross section of the test section(s) and the control section(s), their location, length, and condition, including a crack survey;
3. Subgrade, subbase, and base data;
4. Materials data (asphalt cement grade, asphalt cement source, CRM source type and gradation (size), aggregate types and gradations, etc.);
5. Mix designs;
6. Results of materials and design testing; and
7. Special design of materials, concerns, or features.

CONSTRUCTION PROCEDURES

The following information should be collected during the CRM asphalt paving and conventional asphalt paving:

1. Plant operations:
    (1) Plant type and needed modifications
    (2) Mix temperatures;
2. Mix control testing results (gradations, extractions, stabilities, VMA, etc.);
3. Laydown temperature(s) and densities;
4. Weather conditions;
5. Laydown and compaction equipment used;
6. Worker fumes and stack emissions during construction; and
7. Special construction concerns or features.

PERFORMANCE MONITORING

The following monitoring information should be obtained as appropriate for both the test section(s) and control section(s):

1. Densities and void contents (traffic compaction/action);
2. Rutting;
3. Ravelling;
4. Cracking;
5. Stripping;
6. Deflections (if a significant factor);
7. Roughness;
8. Skid resistance (frictional properties); and
9. Winter ice and snow control.

Visual condition rating is particularly effective at early stage of performance monitoring.

COST

The cost analysis should include a comparison of the component and total costs (dollars per tonne) involved for the CRM asphalt paving and conventional asphalt paving.

ENVIRONMENTAL CONSIDERATIONS

A documented evaluation of emissions and fumes testing results, if appropriate, should be included.

PERFORMANCE MONITORING

There is a need to perform a two-phase evaluation. The first phase would be a detailed and frequent performance monitoring that lasts a suggested minimum of 3 years. The second phase would be a long-term evaluation that would involve selective performance monitoring at periodic intervals throughout the life of the demonstration project.

1. Phase I Reporting:
    - (1) Initial Report: This report should be prepared within 90 days of project completion. It should contain all of the information outlined above, as appropriate;
    - (2) Interim Reports: Information obtained from performance monitoring should be reported annually in a format easily understood, and summarized. If appropriate, it should include any discussions useful in assessment of the CRM asphalt paving;
    - (3) Final Report: This should include a comprehensive summary of all data collected, an overall evaluation of the cost-effectiveness of the CRM asphalt paving, and recommendations based on the information collected.

2. Phase II Reporting:
    - (1) Periodic Progress Reports: After completing Phase I of the evaluation, agencies should continue to monitor the project until pavement failure. Data or information included under performance measurements should be reported every 3 years, or as appropriate; and
    - (2) These periodic progress reports can be similar to the interim reports.

APPENDIX F

KEY CONTACTS

Contacts for Ontario Rubber Modified Asphalt Demonstration Projects

Grey County Road 12 [RUMAC, Grey #1]
Grey County Road 13 [RUMCIP, Grey CIP]
Grey County
Highway Department
County Administration Building
595 - 9th Avenue East
Owen Sound, Ontario N4K 2W3
Telephone (519) 376-7337 Facsimile (519) 376-0967
Department Manager: **Gary Shaw**

Grow-Rich Inc. [Grow-Rich]
Grow-Rich Inc.
8923 Chippewa Road
Niagara Falls, Ontario L2E 6S5
Telephone (905) 357-6421
Marketing Manager: **Ed Ciepiela**

Haldimand-Norfolk Trial #1 [RUMAC, HN #1]
Haldimand-Norfolk Trial #2 [RUMAC, HN #2]
Regional Municipality of Haldimand-Norfolk
Regional Administration Building
70 Town Centre Drive
Townsend, Ontario N0A 1S0
Telephone (519) 587-4911 Facsimile (519) 587-5554
Manager Roads Division: **Nil Lambert**

Ministry of Transportation - Thamesville Phase I [RUMAC, MTO #1]
Ministry of Transportation - Thamesville Phase II [RUMAC, RRUMAC, MTO #2]
Ministry of Transportation
Engineering Materials Office
1201 Wilson Avenue
Downsview, Ontario M3M 1J8
Telephone (416) 235-3725 Facsimile (416) 235-3996
Head, Bituminous Section: **Kai Tam**

Ministry of Transportation - Highway 400 [AR, MTO Wet]
Ministry of Transportation
Research and Development Branch
1201 Wilson Avenue
Downsview, Ontario M3M 1J8
Telephone (416) 235-4701 Facsimile (416) 235-4872
Head, Pavements and Roadways Office: **Gerhard Kennepohl**

Lambton County [RUMCIP, Lambton]
Lambton County
Public Works Department
Box 3000
Wyoming, Ontario N0N 1T0
Telephone (519) 845-0801 Facsimile (519) 845-3160
Director of Public Works: **Doug French**

Halton Region [RUMAC, Halton]
Regional Municipality of Halton
Public Works Department
1151 Bronte Road
Oakville, Ontario L6J 6E1
Telephone (905) 825-6021 Facsimile (905) 825-0267
Landfill Engineer: **Cliff Chan**

Proton Township [RUMAC, Proton]
Proton Township
RR 1
Dundalk, Ontario N0C 1B0
Telephone (519) 923-2110
Road Superintendent: **Glen Scott**

Contacts for General Information on Crumb Rubber Modifier Use in Asphalt Paving

American Association of State Highway and Transportation Officials
444 N. Capitol St., N.W., Suite 249
Washington, DC 20001
Telephone (202) 624-5800 Facsimile (202) 624-5806
Executive Director: **Francis B. Francois**

Asphalt Recycling and Reclaiming Association (ARRA)
#3 Church Circle, Suite 250
Annapolis, Maryland 21401
Telephone (410) 267-0023 Facsimile (410) 267-7546
Executive Director: **Mike Krissoff**

Federal Highway Administration
United States Department of Transportation
Turner-Fairbank Highway Research Center, HNR-20
6300 Georgetown Pike
McLean, Virginia 22101
Telephone (703) 285-2435 Facsimile (703) 285-2791
Chief, Pavement Division: **Byron Lord**
Engineer: **Michael Smith** (703-285-2431)
Application Team Leader: **Jim Sorenson** (202-366-1333)

National Center for Asphalt Technology (NCAT)
Auburn University
211 Ramsay Hall
Auburn, Alabama 36849
Telephone (205) 844-6228 Facsimile (205) 844-6248
Executive Director: **Ray Brown**

National Asphalt Pavement Association (NAPA)
5100 Forbes Boulevard
Lanham, Maryland 20706
Telephone (301) 731-4748 Facsimile (301) 731-4621
President: Mike Acott
Assistant Director of Environmental and Safety Services: **John Rugg**

New Jersey Department of Transportation
Division of Research and Demonstration
1035 Parkway Avenue, CN 612
Trenton, New Jersey 08625
Telephone (609) 292-5730 Facsimile (609) 292-4599
Research Engineer: **Robert Baker**

Rouse Rubber Industries, Inc.
Post Office Box 820369
Vicksburg, Mississippi 39182
Telephone (601) 636-7141 Facsimile (601) 636-1181
President: **Michael Wm. Rouse**

Rubber Pavements Association (previously the Asphalt Rubber Producers Group)
312 Massachusetts Avenue, NE
Washington, DC 20002
Telephone (202) 544-7111 Facsimile (202) 544-7146
Director of Public Affairs: **Sean Reed**

Scrap Tire Management Council
1400 K Street, N.W.
Washington, DC 20005
Telephone (202) 408-7781 Facsimile (202) 682-4854
Executive Director: **Michael Blumenthal**

State of Florida Department of Transportation
State Materials Office
2006 N.E. Waldo Road (Post Office Box 1029)
Gainesville, Florida 32602
Telephone (904) 372-5304 Facsimile (904) 334-1649
State Bituminous Materials Engineer: **Gale Page**

Strategic Highway Research Program
National Research Council
818 Connecticut Avenue, N.W.
Washington, DC 20006
Telephone (202) 334-3774 Facsimile (202) 223-2875
Executive Director: **Damian Kulash**

Sources of Crumb Rubber Modifier in Ontario

National Rubber Company Inc. (Ambient Process CRM)
394 Synington Avenue
Toronto, Ontario M6N 2W3
Telephone (416) 657-1111 Facsimile (416) 652-4212
Vice President - Marketing and Sales: **Toby O'Brien**

Recovery Technologies Inc. [Cryogenic Process CRM]
5925 Airport Road, Suite 612
Mississauga, Ontario L4V 1W1
Telephone (905) 672-9448 Facsimile (905) 673-8538
Sales Manager: **Robert Kover**

T/W/R Inc. (Ambient Process CRM)
85 Passmore Avenue
P.O. Box 272
Agincourt, Ontario M1S 3B6
Telephone (416) 291-3519 Facsimile (416) 291-3252
Sales Manager: **Carmela Rogers**

APPENDIX G

ABBREVIATIONS

3Rs	reduce, reuse and recycle
AC	asphalt cement
ACRM	ambient (process) crumb rubber modifier
AI	Asphalt Institute
AR	asphalt rubber (often referred to as wet process)
ARB	asphalt rubber binder
ARHMA	asphalt rubber hot-mix asphalt (asphalt concrete)
ARPG	Asphalt Rubber Producers Group
ARRA	Asphalt Recycling and Reclaiming Association
ASTM	American Society for Testing and Materials
CARB	California Air Resources Branch
CCRM	cryogenic (process) crumb rubber modifier
CGSB	Canadian General Standards Board
CIP	cold in-place recycling
CRM	crumb rubber modifier
CRREL	Cold Regions Research and Engineering Laboratory (United States Army Corps of Engineers)
CSA	Canadian Standards Association
EPA	United States Environmental Protection Agency
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration, Unites States Department of Transportation
GTA	Greater Toronto Area
GTR	ground tire rubber
HIP	hot in-place recycling
HMA	hot-mix asphalt (hot-mix asphalt concrete)
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991 (United States)
JEGEL	John Emery Geotechnical Engineering Limited
JMF	job mix formula
MAPS	Mobile Air Pollution System
MIBK	4-Methyl-2-pentanone
MNR	Ontario Ministry of Natural Resources
MOEE	Ontario Ministry of Environment and Energy (formerly MOE)
MT	Metro Transportation (Municipality of Metropolitan Toronto Transportation Department)
MTO	Ontario Ministry of Transportation (formerly MTC)
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NJDOT	New Jersey Department of Transportation
OHMPA	Ontario Hot Mix Producers Association
OPSS	Ontario Provincial Standard Specification

ORBA	Ontario Road Builders Association
PAH	polynuclear aromatic hydrocarbon
PCC	Portland Cement Concrete
RAM	reclaimed aggregate material
RAP	reclaimed asphalt pavement
RARAC	recycled asphalt rubber asphalt concrete (hot-mix asphalt)
RHM	recycled hot mix
RPA	Rubber Pavements Association (successor to Asphalt Rubber Producers Group)
RRUMAC	recycled rubber modified asphalt concrete (hot-mix asphalt)
RUMAC	rubber modified asphalt concrete (hot-mix asphalt; often referred to as dry process)
RUMCIP	rubber modified cold in-place recycling
RUMHIP	rubber modified hot in-place recycling
SAM	stress absorbing membrane
SAMI	stress absorbing membrane interlayer
SP	special provision
TAC	Transportation Association of Canada
TCLP	Toxic Characteristic Leachability Procedure
VOC	Volatile Organic Compound
VOST	Volatile Organic Sampling Train

APPENDIX H

METRIC CONVERSIONS

1 kilometre (km) = 0.6214 miles (statute)
1 metre (m) = 3.2808 feet
1 millimetre (mm) = 0.0397 inches
1 micrometre (μm) = 3.97×10^{-5} inches
1 hectare (ha) = 2.4711 acres
1 square metre (m^2) = 10.7639 square feet
1 cubic metre (m^3) = 1.3080 cubic yards
1 litre (ℓ) = 0.2200 gallons (imperial)
1 kilogram (kg) = 2.2046 pounds
1 metric tonne (t) or (Mg) = 1.1023 short tons
= 2204.6 pounds

Celsius temperature (°C) 1.8°C+32 Fahrenheit temperature (°F)

4.75 mm sieve (ASTM E-11)	No. 4 sieve (4 mesh)
2.00 mm sieve	No. 10 sieve (10 mesh)
850 μm sieve	No. 20 sieve (20 mesh)
600 μm sieve	No. 30 sieve (30 mesh)
425 μm sieve	No. 40 sieve (40 mesh)
300 μm sieve	No. 50 sieve (50 mesh)
180 μm sieve	No. 80 sieve (80 mesh)
150 μm sieve	No. 100 sieve (100 mesh)
75 μm sieve	No. 200 sieve (200 mesh)